# Towards a consistent jet quenching picture at RHIC (and LHC ?)

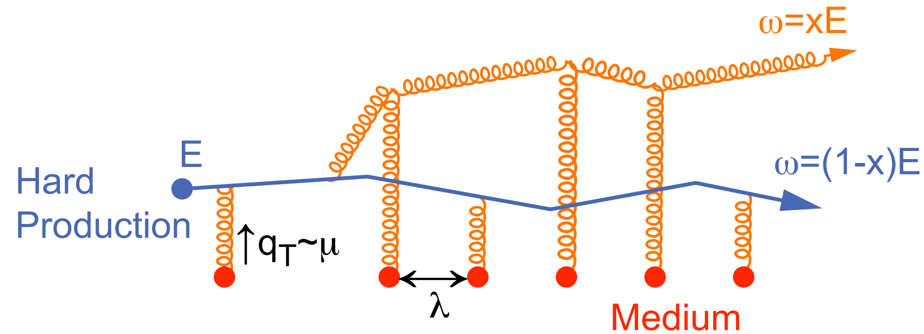
Jörn Putschke

(Yale University)

# Jet-quenching theory from an experimentalists view

## Gluon radiation

Multiple final-state gluon radiation off of the produced hard parton induced by the traversed dense colored medium




| General form: | Partonic spectrum $E_{jet}$ | ⊗ | Nuclear geometry $L$ | ⊗ | Energy loss $\Delta E(E_{jet})$ | ⊗ | Fragmentation $D(E_{jet}, \Delta E)$ |
|---|---|---|---|---|---|---|---|

- Mean parton energy loss $\propto$ medium properties:
  - $\Delta E \sim \rho_{gluon}$ (gluon density)
  - $\Delta E \sim \Delta L^2$ (medium length)
    $\Rightarrow \sim \Delta L$ with expansion

- Characterization of medium via transport coefficient $\hat{q}$ is mean $p_T^2$ transferred from the medium to a hard gluon per unit path length λ

A lot of theories/models on the market:

$$\boxed{\hat{q} \sim 2\text{-}10\ \text{GeV/fm}}$$

no quantitive agreement* (based on the available measurements) at RHIC so far!

Naive summary:
To varying extent all theories (except AdS/CFT) predict a **softening** of the fragmentation and an overall **broadening** of the jet shape!

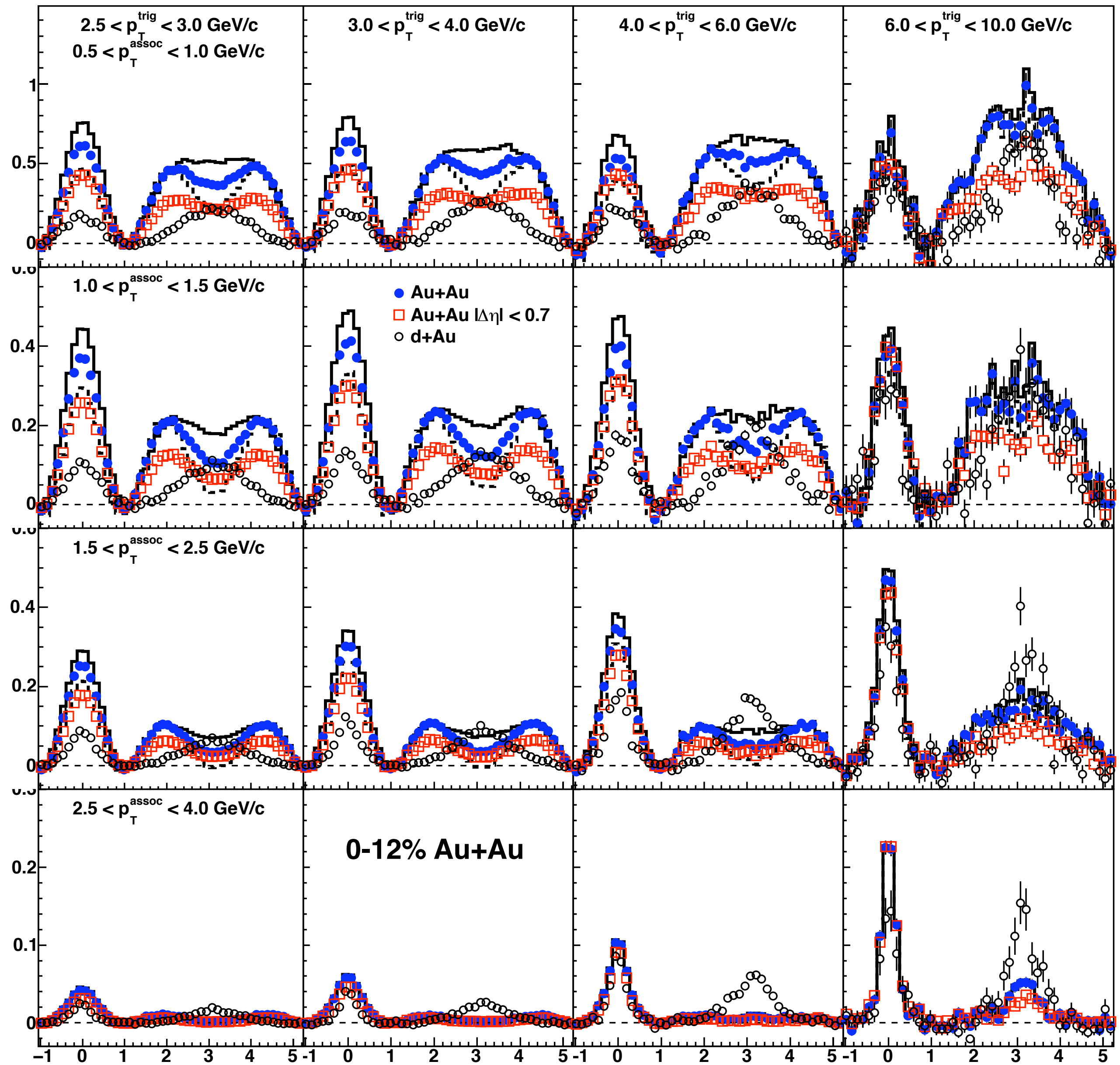
*Remark: The differences might be due to NLO corrections !? (Thesis and *Nucl.Phys.A820:115C-118C,2009)*

# Reminder: Di-hadron correlations systematics

*STAR, arXiv 1004.2377*

Increasing $p_{t,trigger}$

Increasing $p_{t,assoc}$



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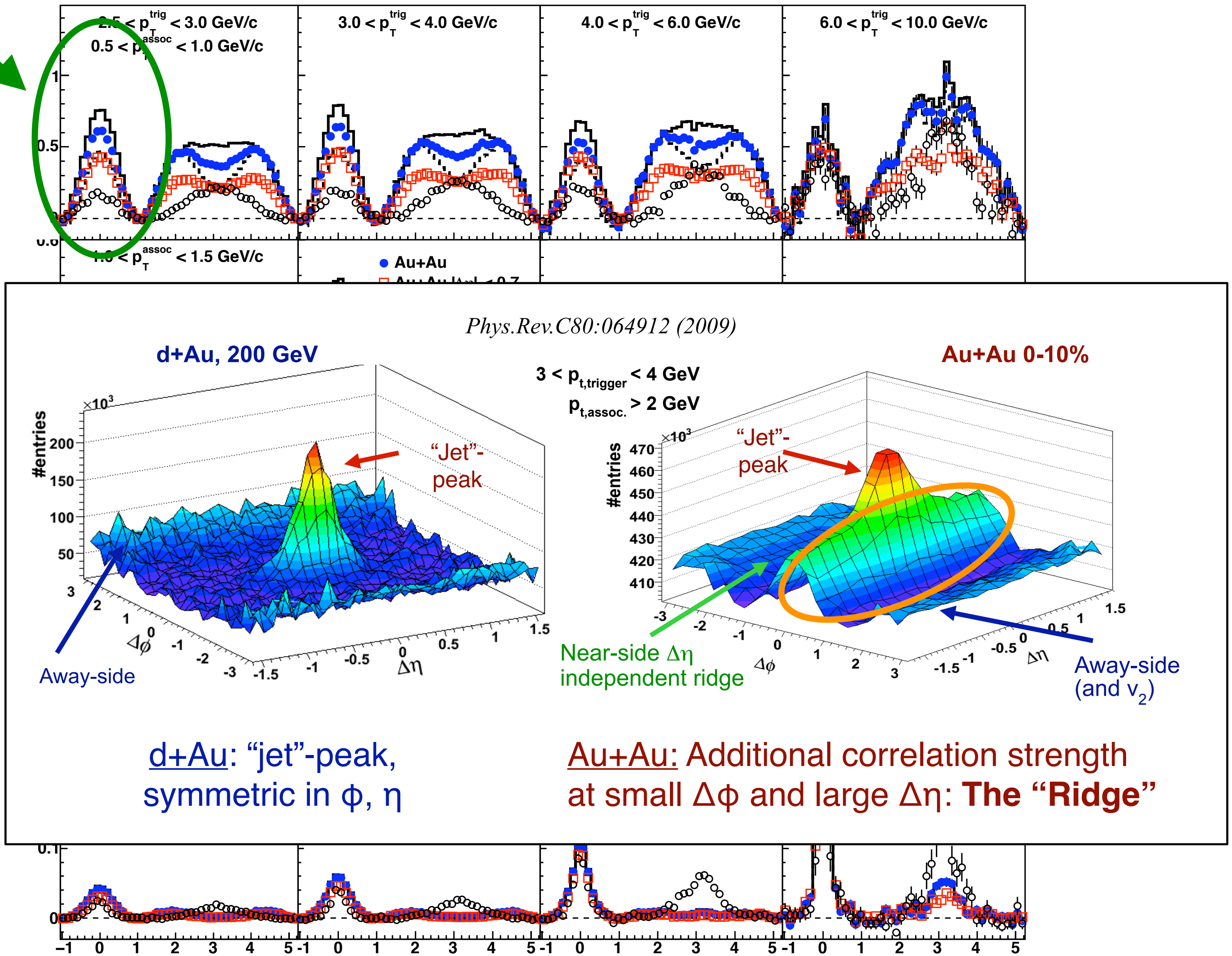
**The "Ridge"**

Increasing $p_{t,assoc}$



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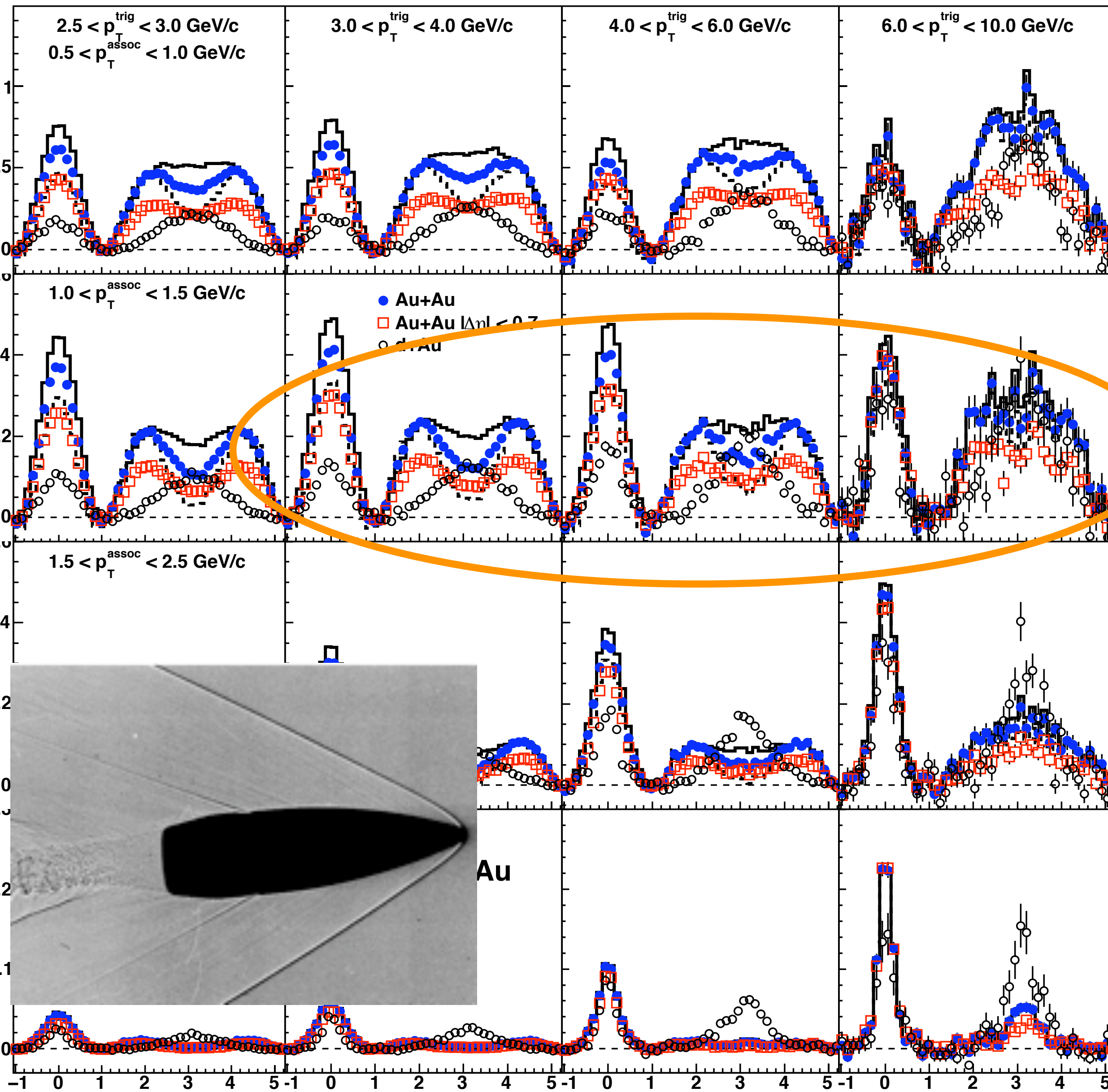
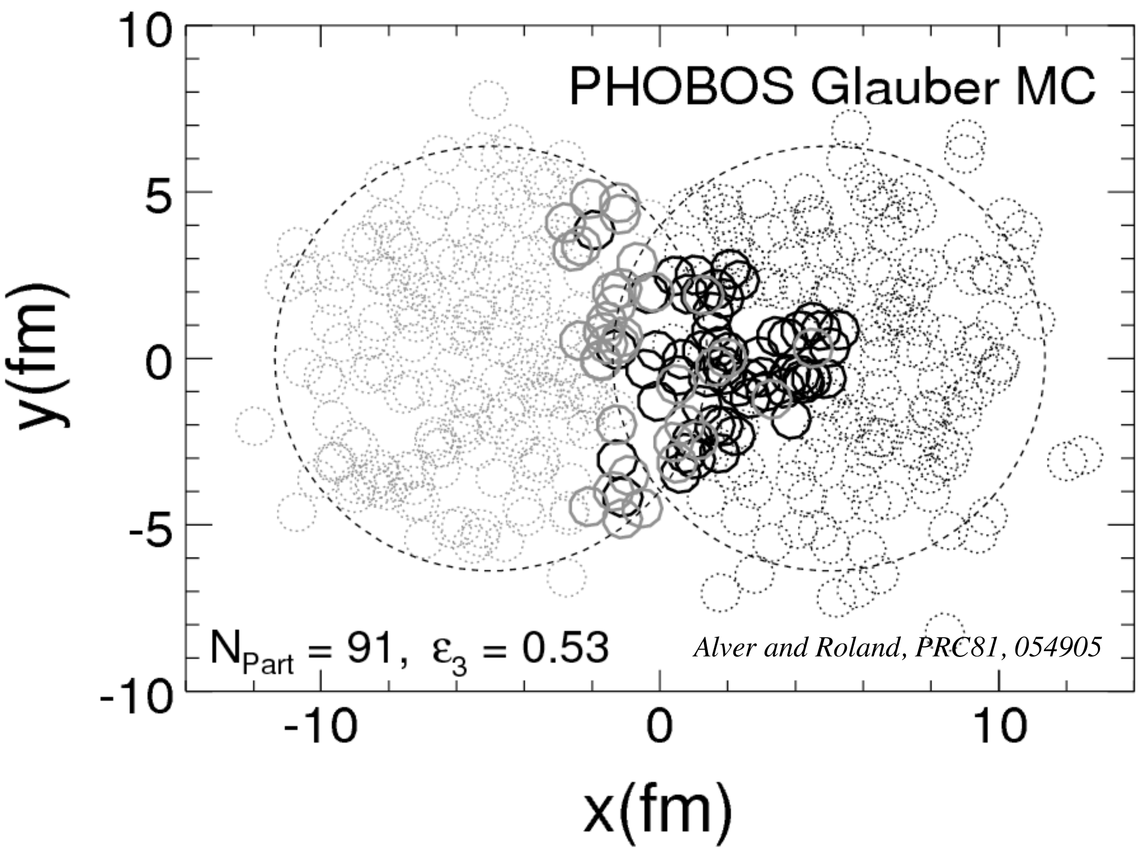



**The "Mach-Cone"! Away-side structure dep. on $p_T^{Trig}$!**

# An elegant solution (QM11): higher harmonics ($v_3$)



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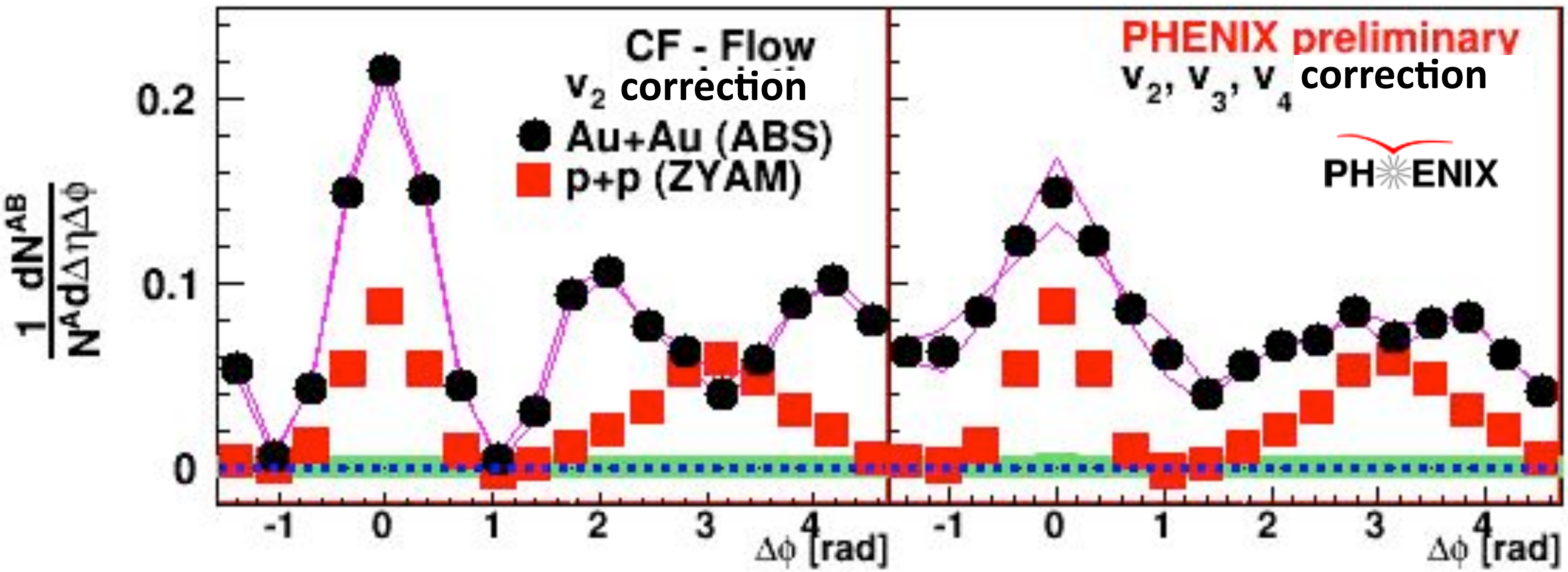
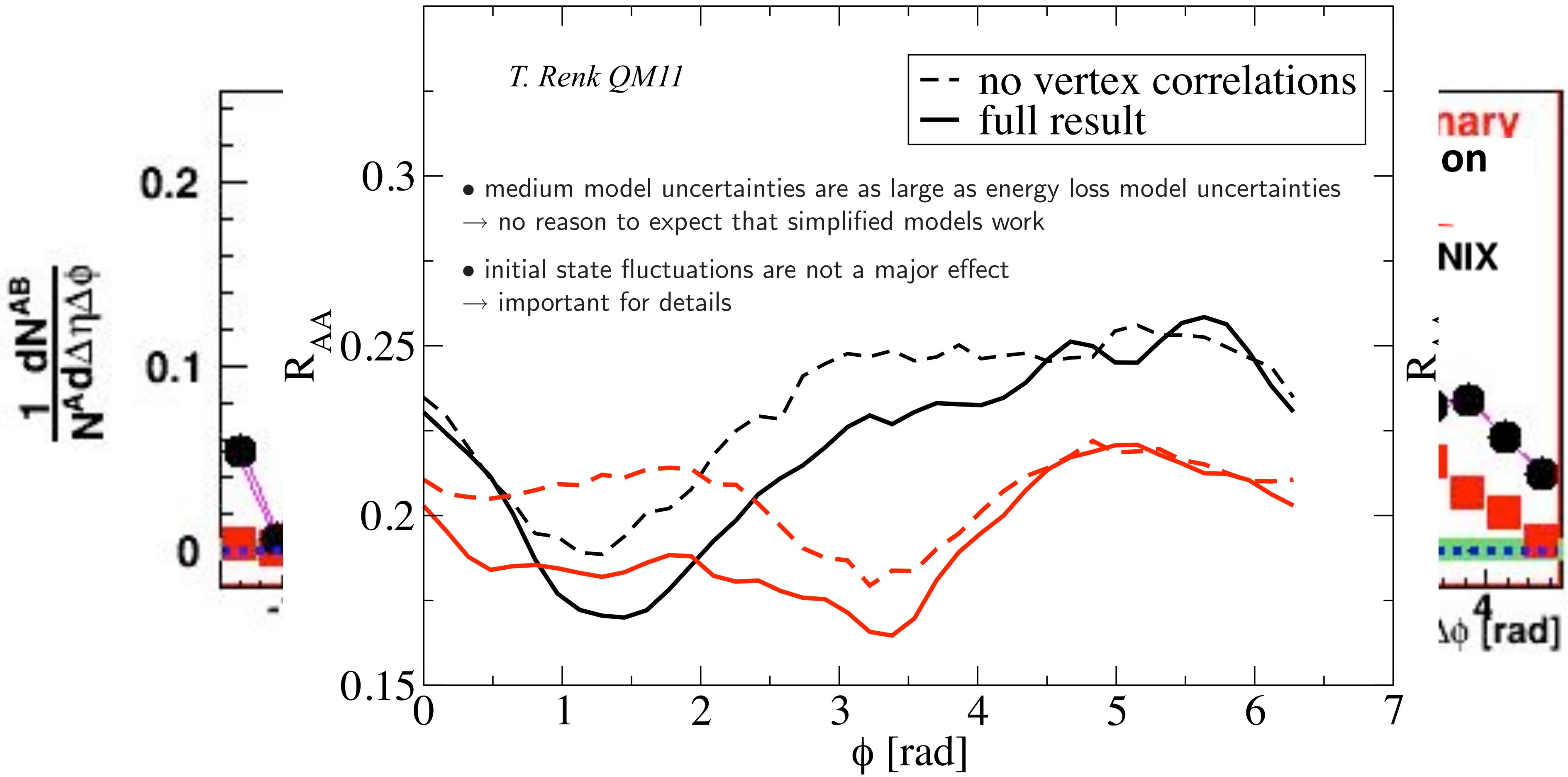



**Higher harmonics seem to describe consistently the "Mach Cone" and the "Ridge" at the same time!**

# An elegant solution (QM11): higher harmonics ($v_3$)




**Higher harmonics seem to describe consistently the "Mach Cone" and the "Ridge" at the same time!**

**Effect of higher harmonics on jets/jet-quenching not yet experimentally measured. From theory: small effect !?**

# Constraining the parton kinematics

**$R_{AA}$ and Di-hadrons are <u>indirect</u> measurements of jet quenching !**

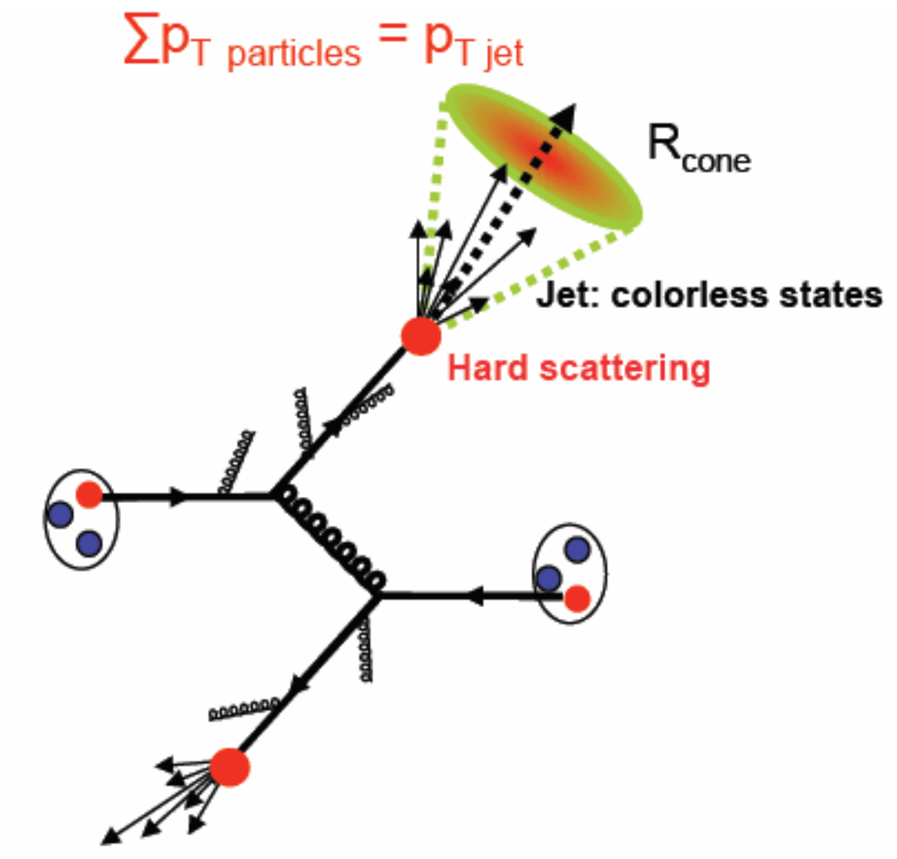
**To study the full spectrum of jet quenching in an unbiased way:**

**<u>Two approaches:</u>**

**1. $\gamma$-jet:** clean, but limited kinematic reach due to x-section

**2. Full jet reconstruction:** large kinematic reach, but complex analysis

# Jets connect theory and experiment




Jets are the experimental signatures of quarks and gluons. They reflect the kinematics and “topology” of partons.

Goal: re-associate (measurable) hadrons to accurately reconstruct partonic kinematics

- pQCD calculates partons
- experiments measure fragments of partons: hadrons

Tool: *Jet-finding algorithms:*
Apply same algorithm to data and theoretical calculations

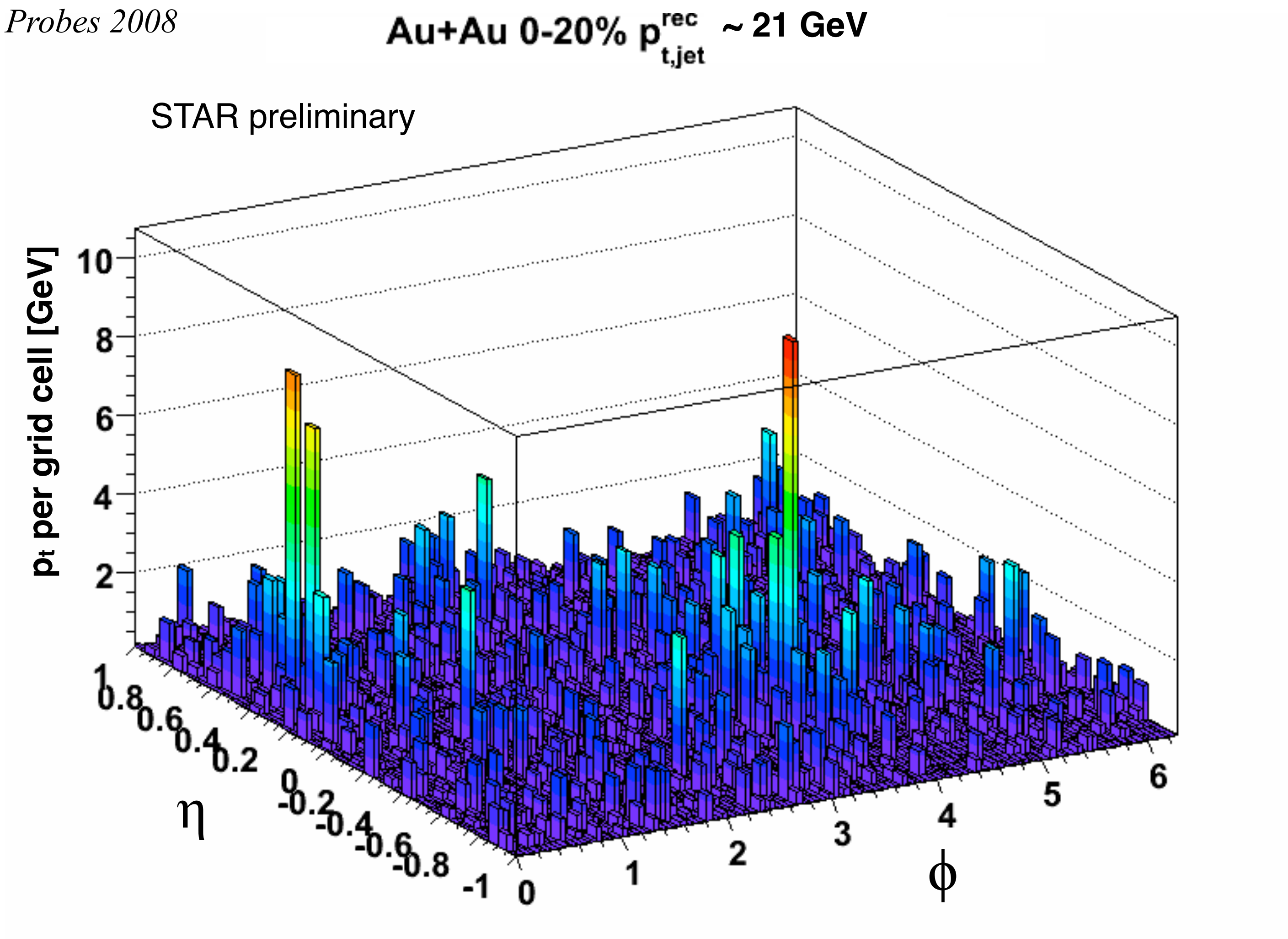
**pQCD factorization/jet spectrum:**

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\rightarrow cd}}{dt}$$

**PDF** **Partonic x-section**

# For the first time in HI collisions: Jets @ RHIC

*STAR, Hard Probes 2008*




- Full jet reconstruction in HI collisions is a challenge due to the underlying background
- <$p_t$(bkg)> ~ 45 GeV for a cone of R=0.4 in central Au+Au collisions
- Region-to-region background fluctuations ~6-7 GeV (gaussian approx.) for a R=0.4

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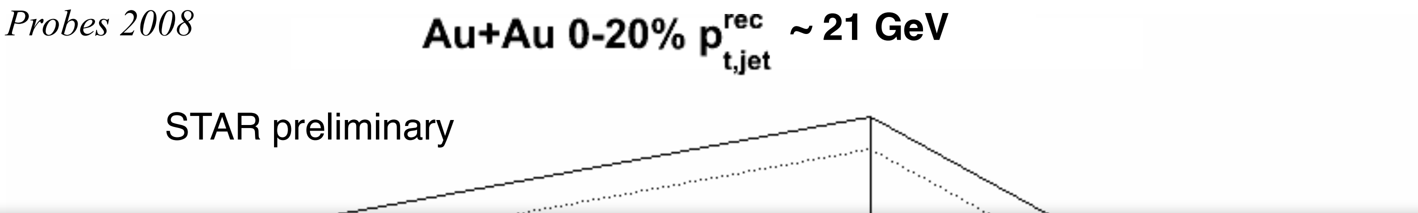


**I will not go into detail on how to correct for background/fluctuations in jet-reconstruction in heavy-ion collisions ...**

**Significant progress has been made and most of the tools are available!**

**There are still open issues which need to be addressed and quantified to look for consistency between different approaches!**

- Full jet reconstruction in HI collisions is a challenge due to the underlying background
- $<p_t(bkg)>$ ~ 45 GeV for a cone of R=0.4 in central Au+Au collisions
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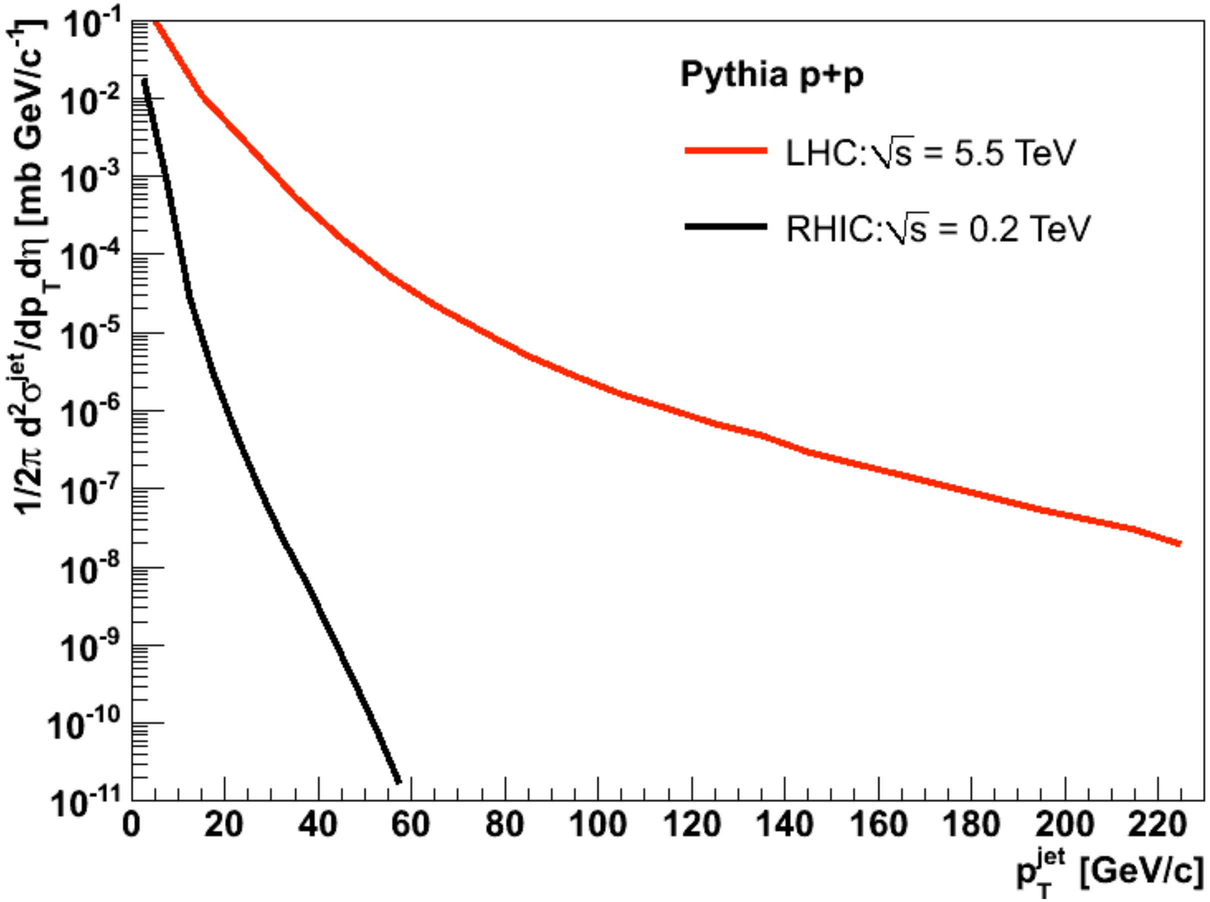
# Effect of background fluctuations at RHIC and LHC

**Toy model: use the independent emission model and p+p x-section**



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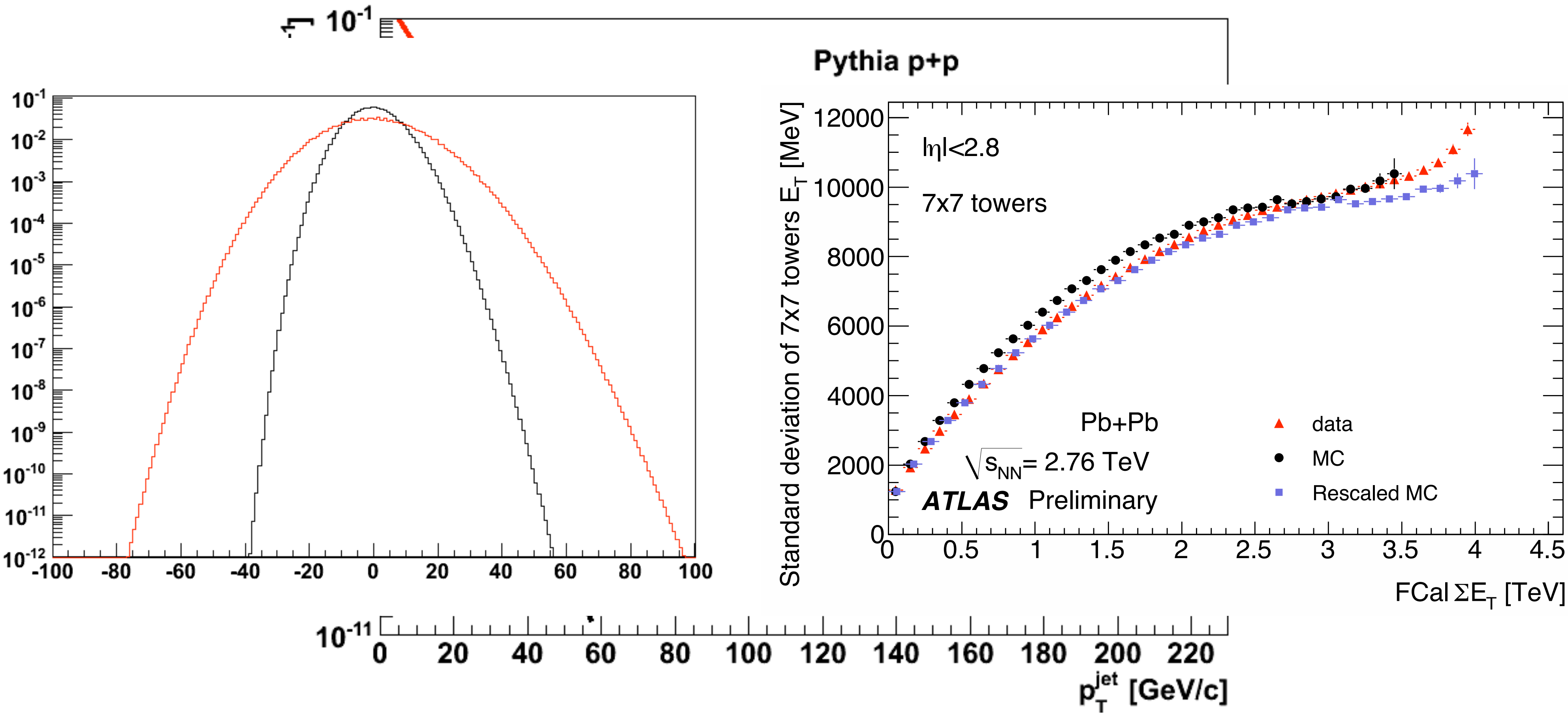

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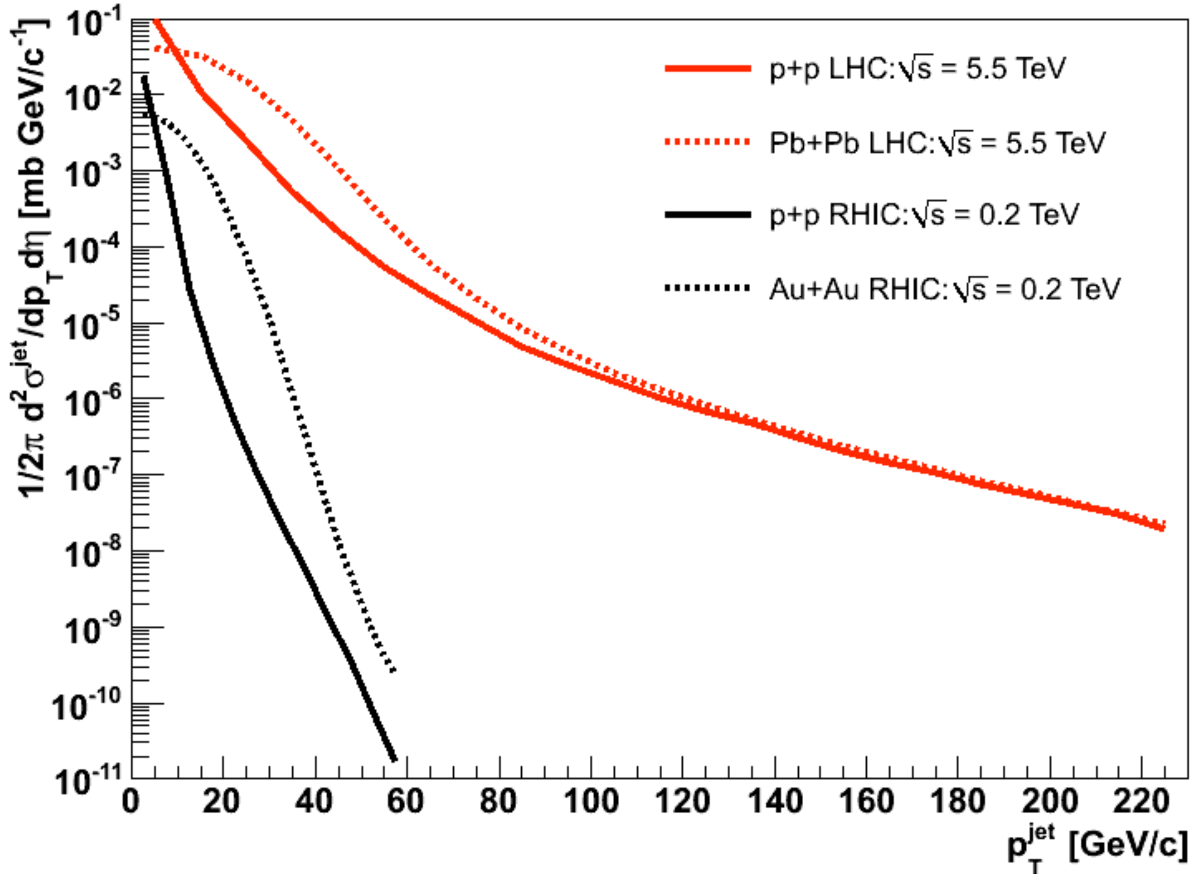

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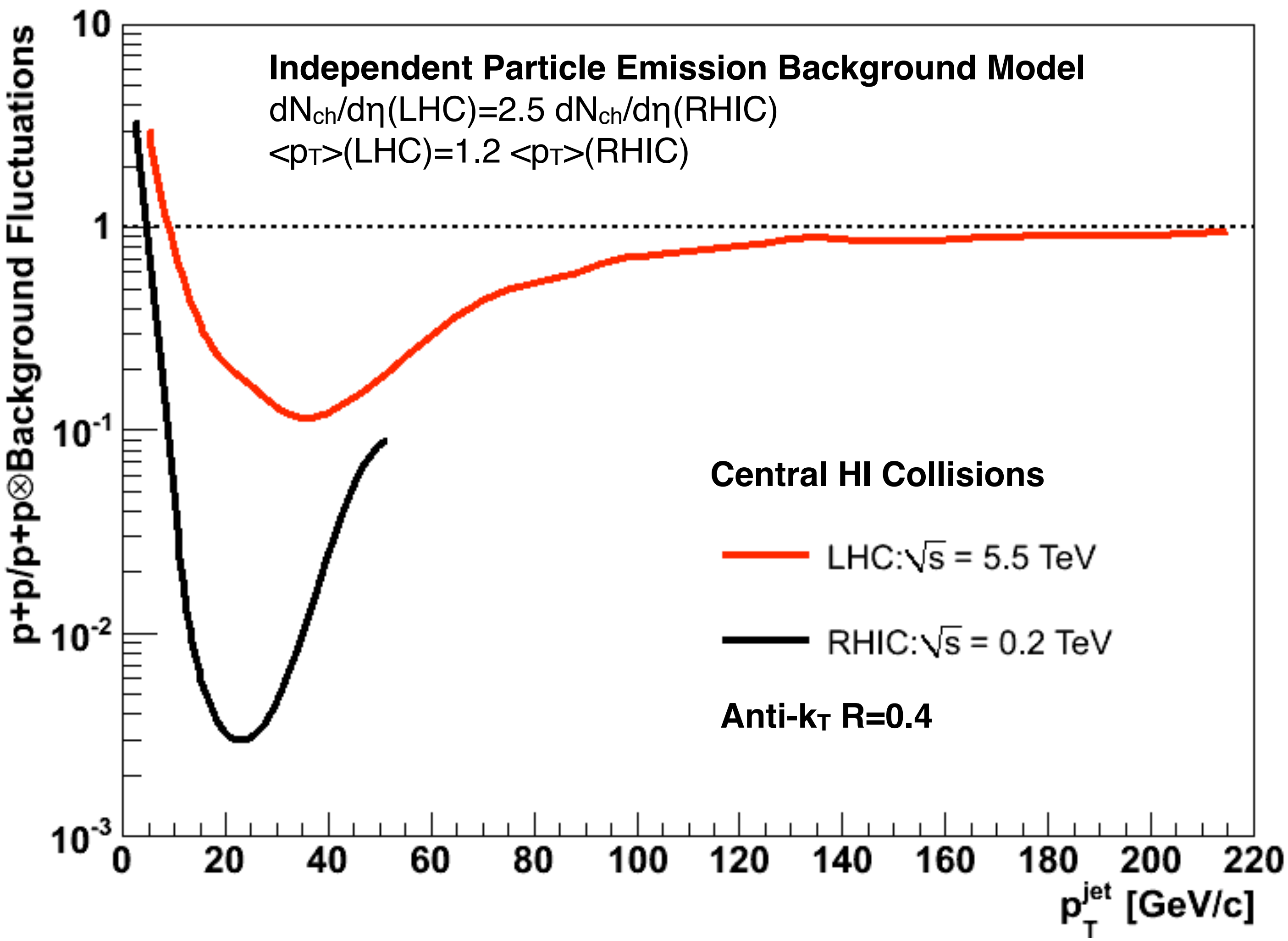
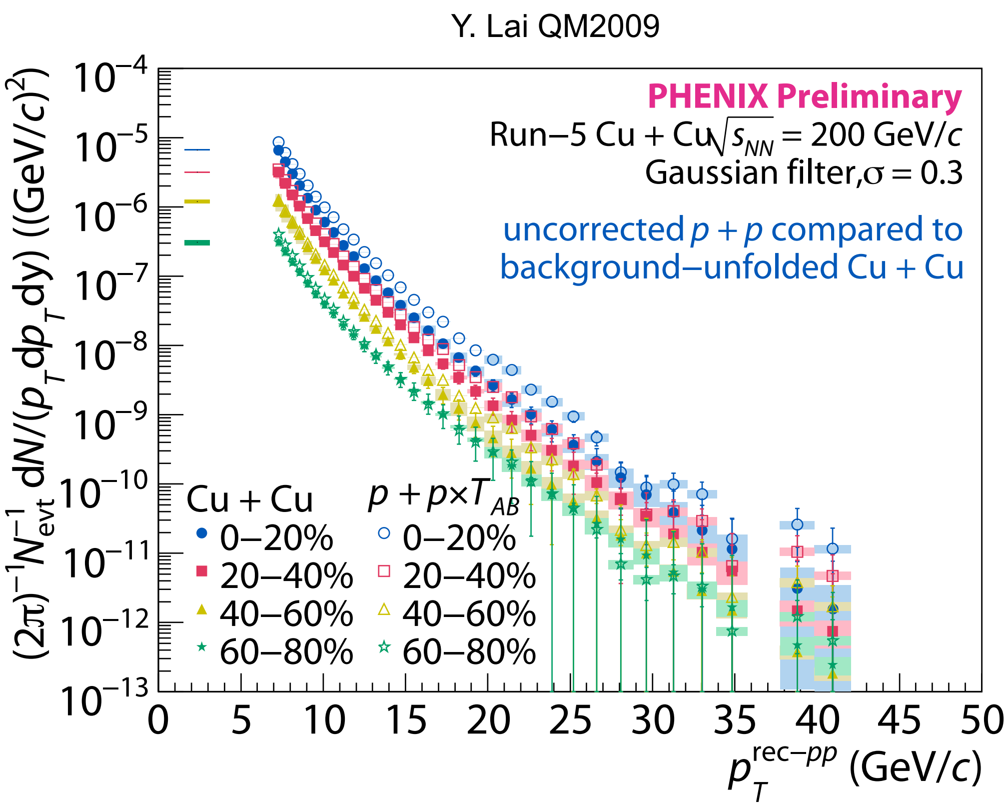
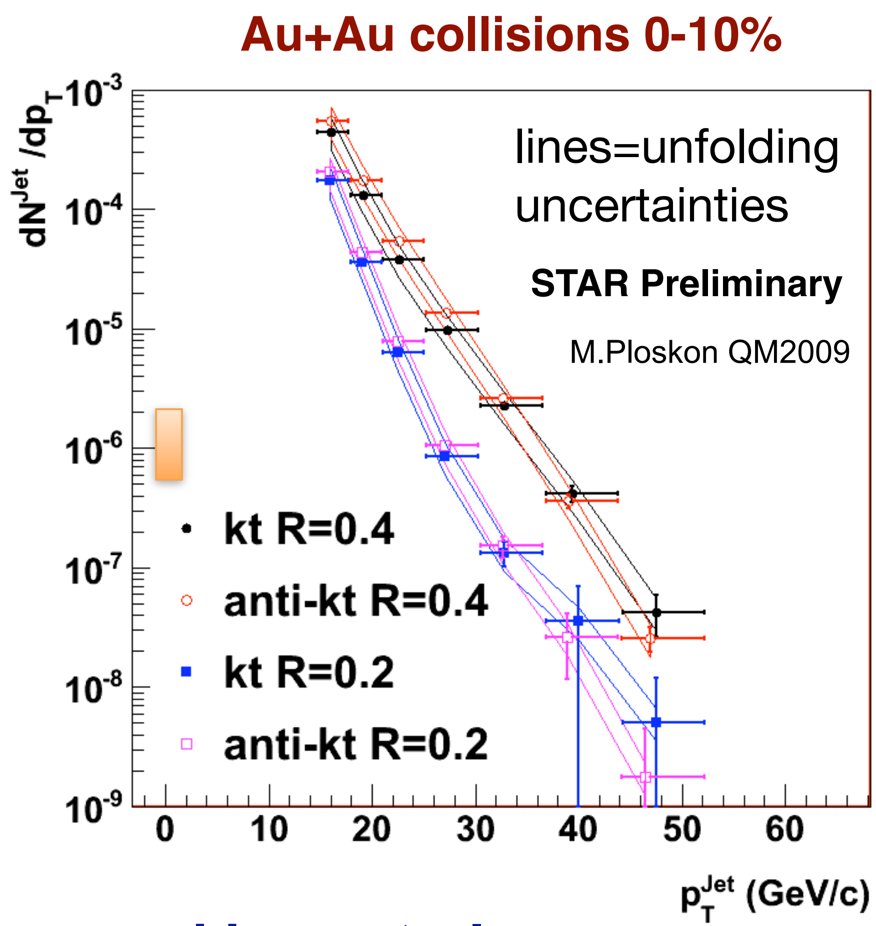



**Fluctuations at RHIC dominant due to steeply falling spectrum**

**Small effect on inclusive jet x-section at the LHC for $p_T^{Jet}$>100 GeV/c**

# Inclusive jet x-section in heavy-ion collisions



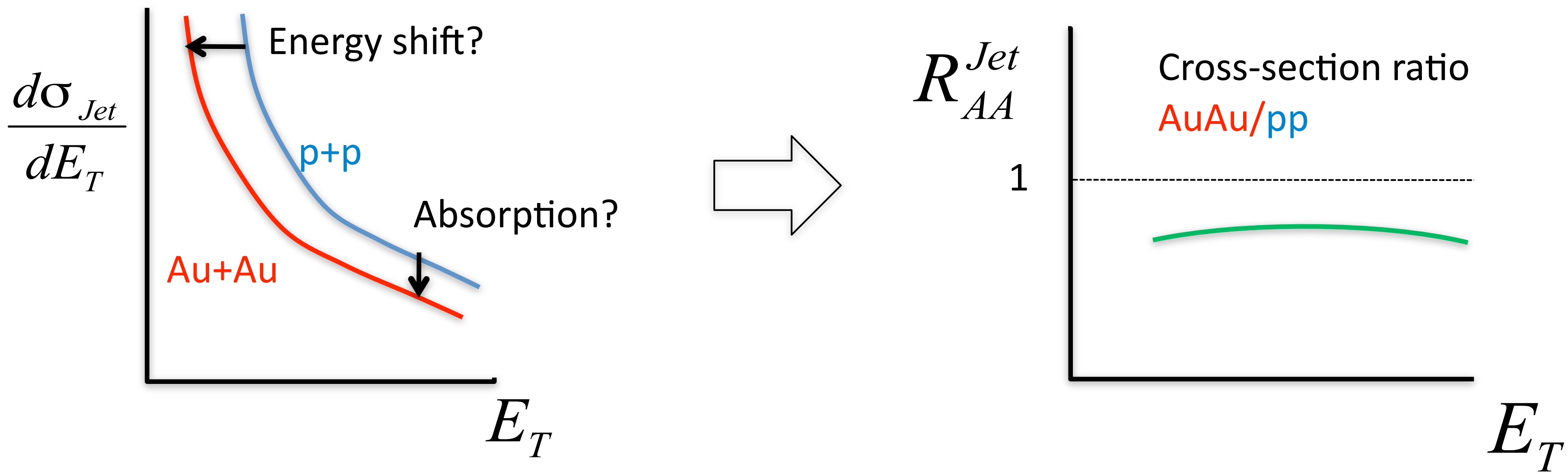




- **Inclusive Jet spectrum measured in central Au+Au and Cu+Cu collisions at RHIC**

- **Extended the kinematical reach to study jet quenching phenomena to jet energies > 40 GeV**

Remark: New high statistics Au+Au runs on tape (Phenix and STAR) will increase significantly the kinematic reach!

# What do we learn from the Au+Au jet spectrum ?

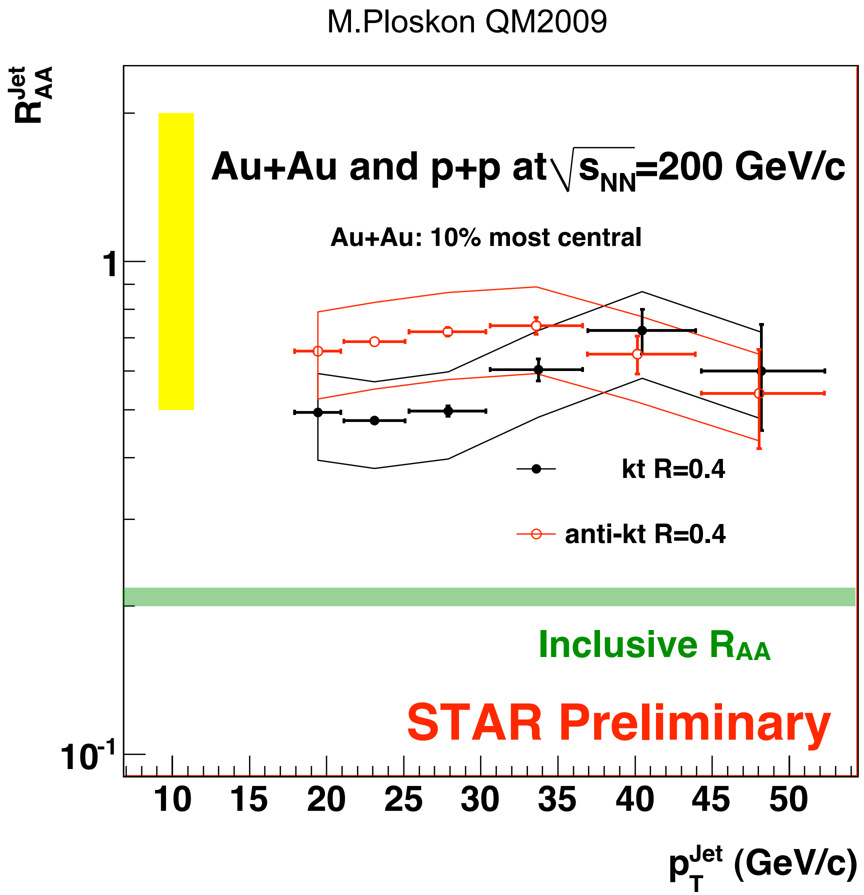


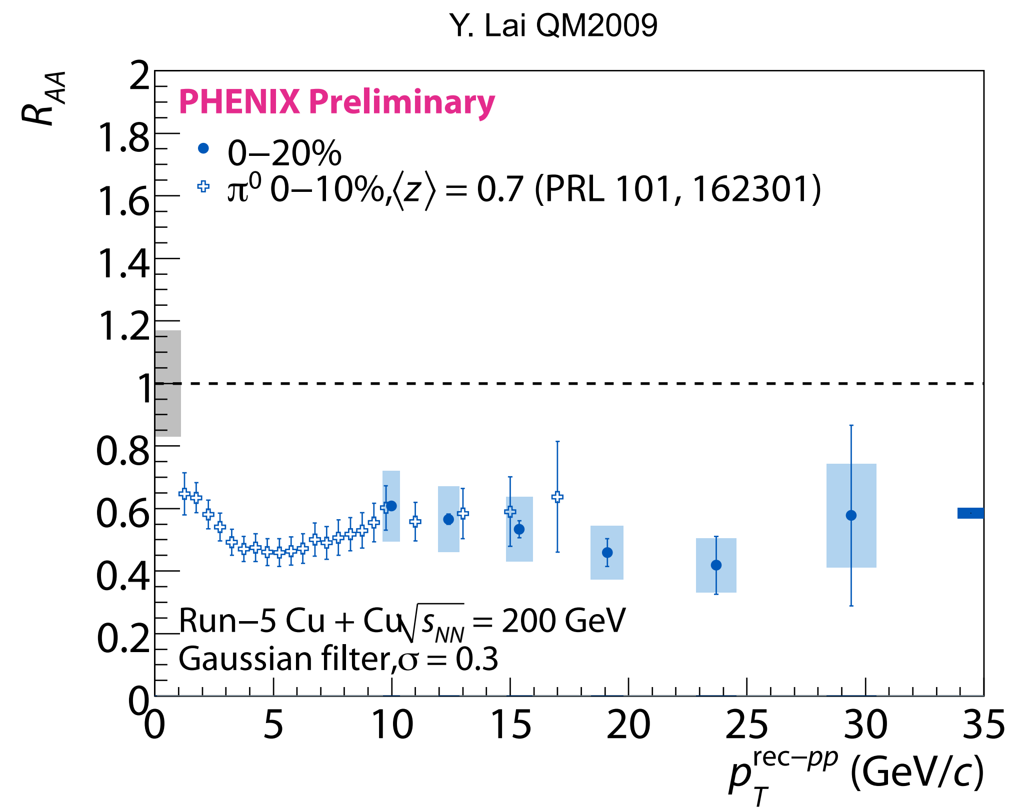

**Momentum and energy is conserved even for quenched jets**

**If full jet reconstruction in heavy-ion collisions is unbiased**

**⇒ Inclusive jet spectrum scales with $N_{coll}$ relative to p+p**

# Jet $R_{AA}$ in central Au+Au and Cu+Cu



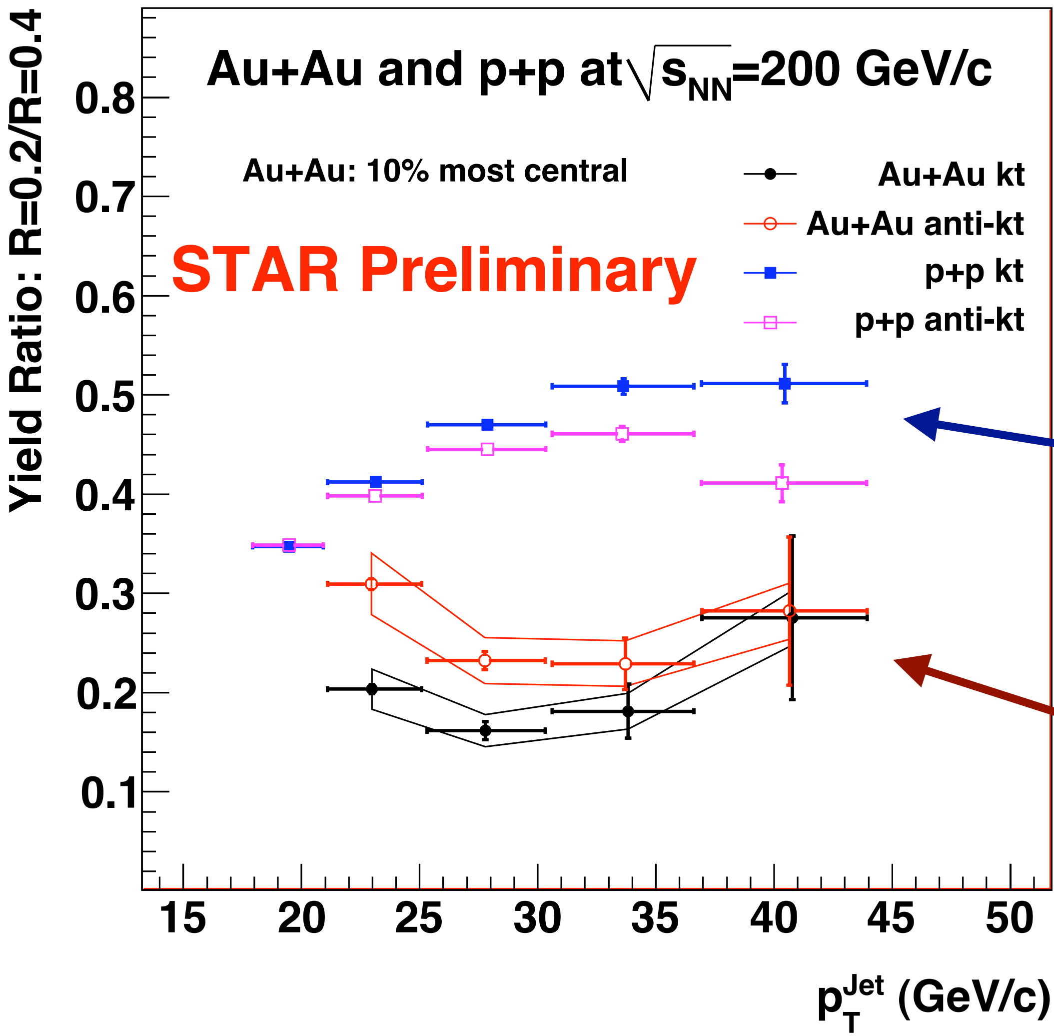



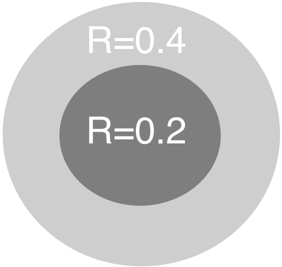

**STAR sees a substantial fraction of jets in Au+Au**
**- in contrast to x5 suppression for light hadron $R_{AA}$**

**Strong suppression (similar to single particle)**
**in Cu+Cu measured by PHENIX**

# First look at the jet energy profile

M.Ploskon QM2009



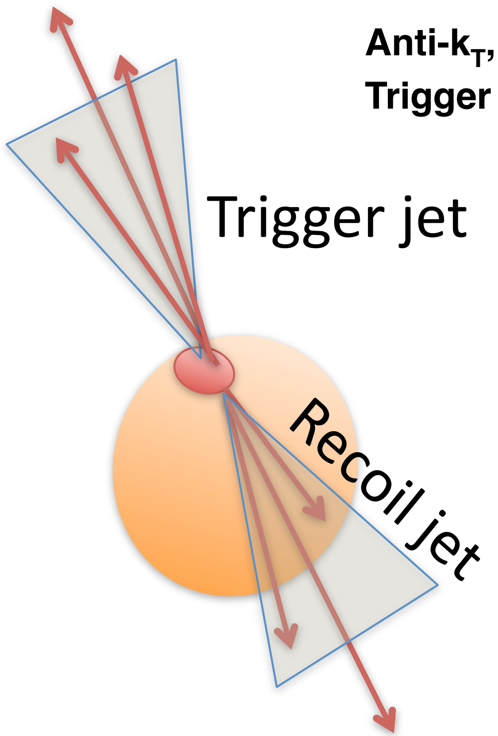




<u>p+p:</u> "Narrowing" of the jet structure with increasing jet energy

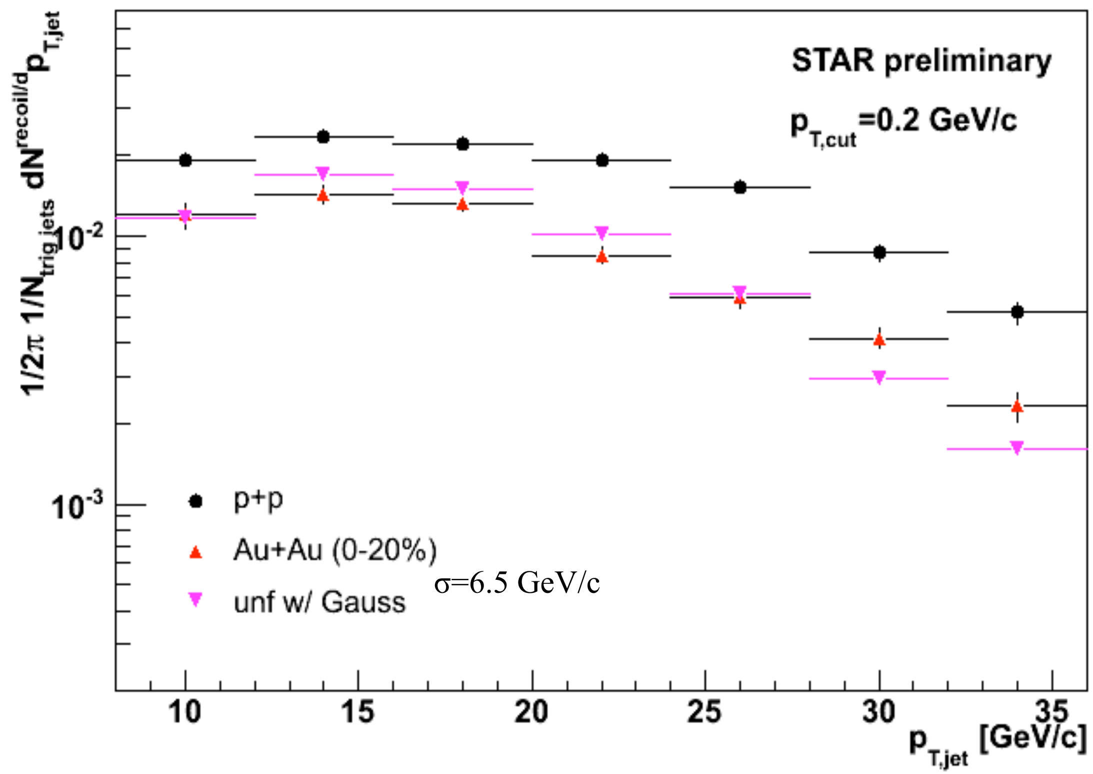
<u>Au+Au:</u> "Deficit" of jet energy of jets reconstructed with R=0.2

**Strong evidence of broadening in the jet energy profile**

# Advantage of recoil jet spectrum measurements




**Anti-$k_T$, R=0.4**
**Trigger Jet: $p_{T,cut}$=2 GeV/c, $p_T$(trig)>20 GeV/c**




**High-$p_T$ trigger jet selection → Flatter spectrum of recoil jets**

**⇒ reduces the sensitivity to details of background fluctuations!**

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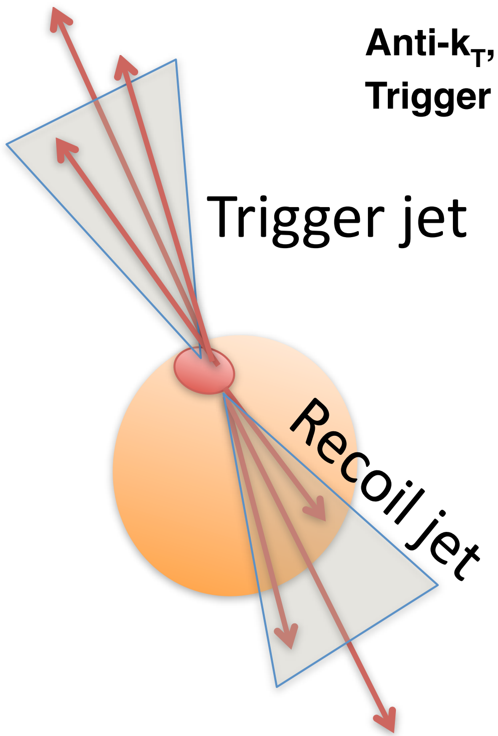


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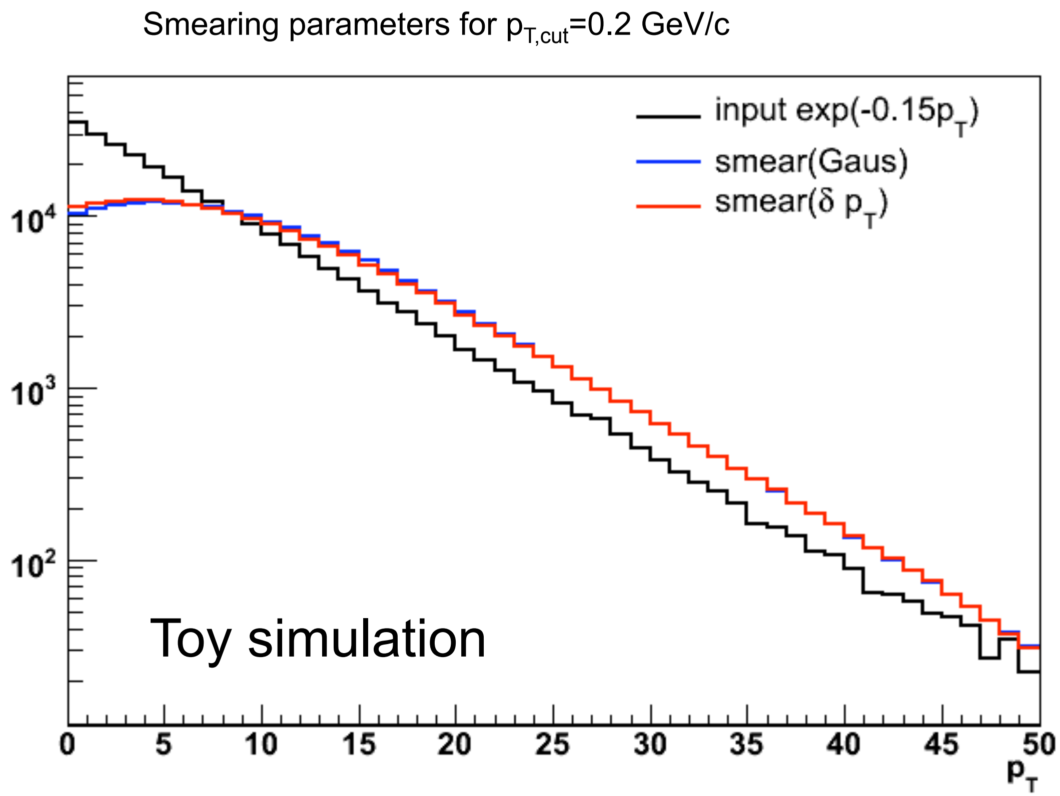


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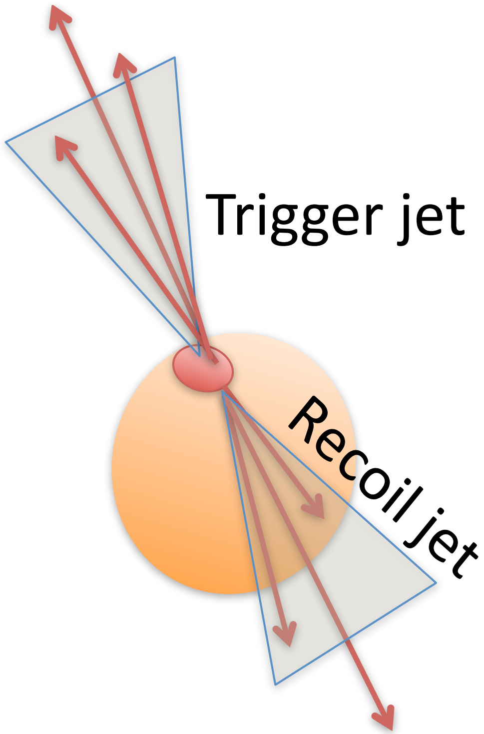
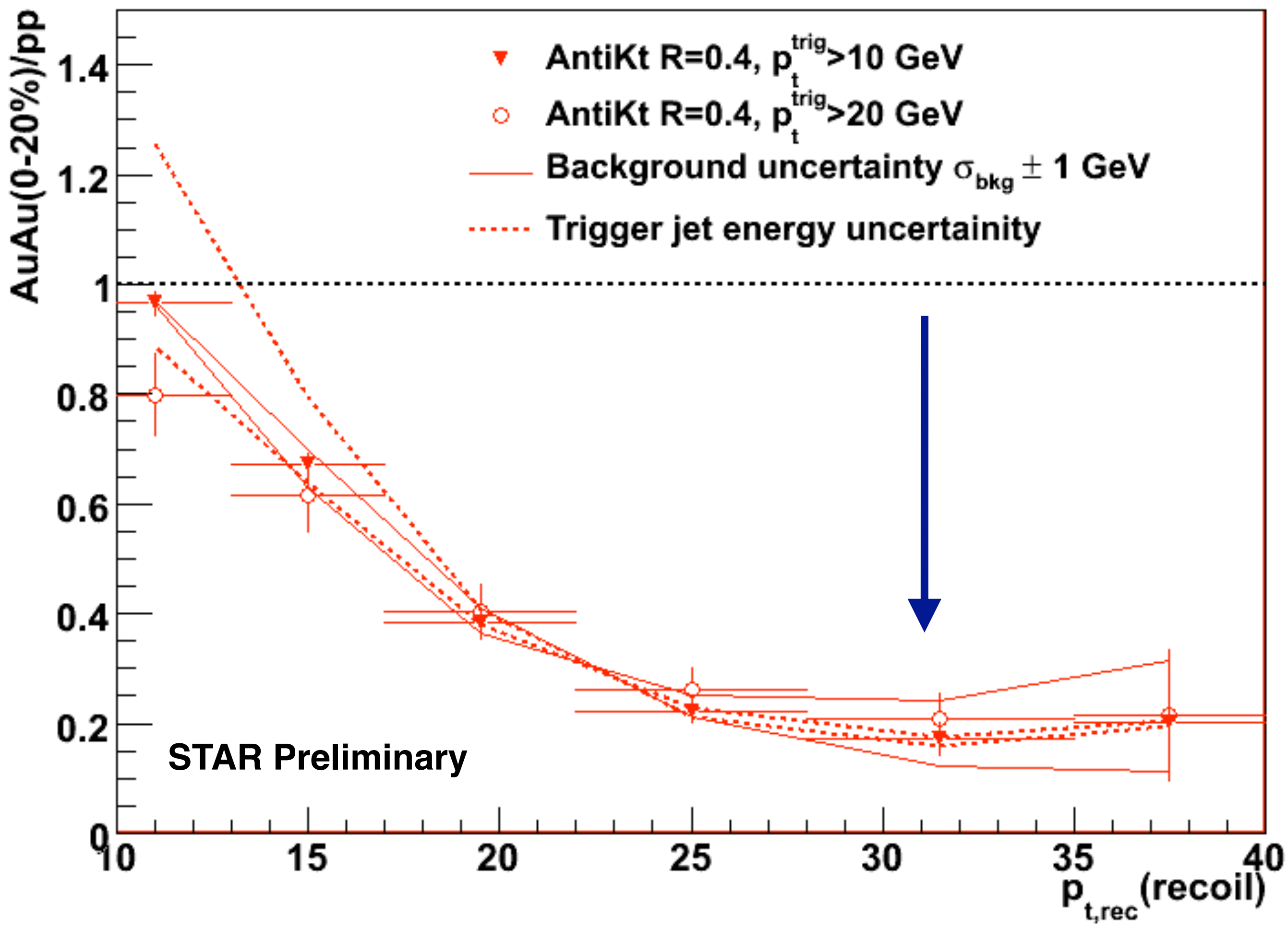
# Recoil jet spectrum $R_{AA}$

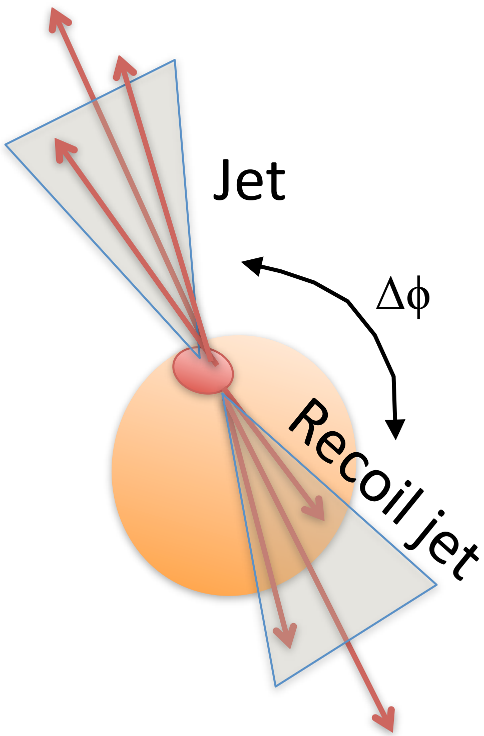


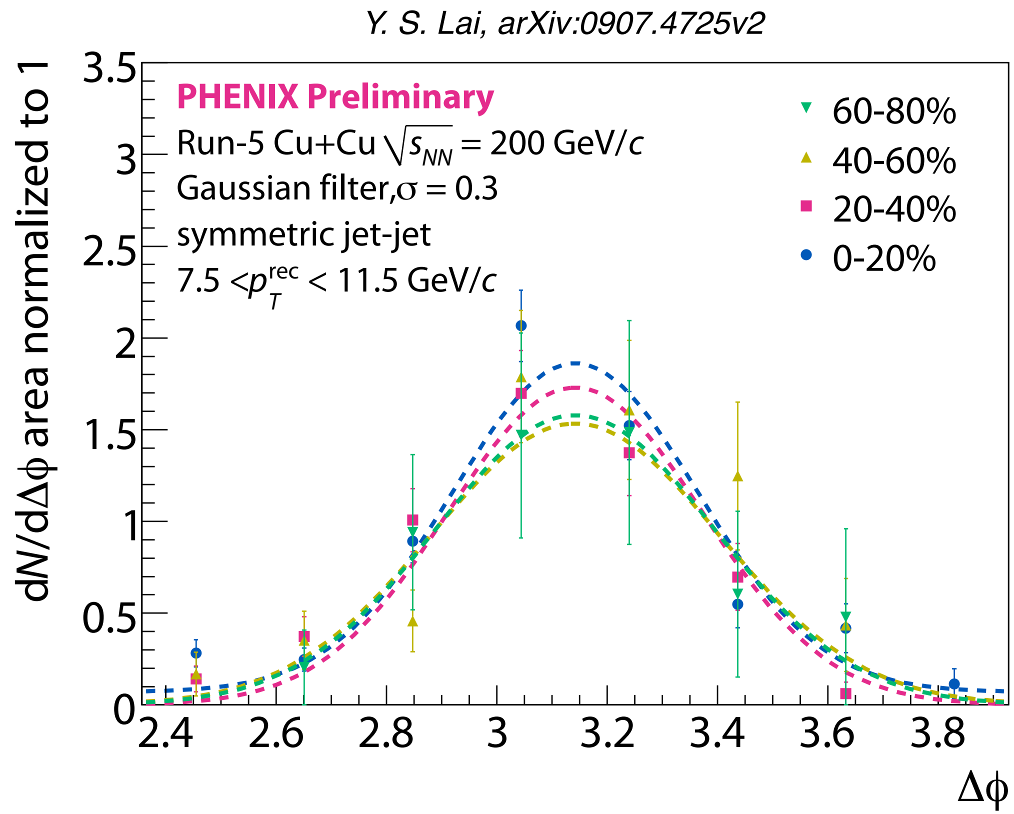

E. Bruna QM2009




- **Selecting biased trigger jet maximizes pathlength for the back-to-back jets: *extreme selection of jet population***
- **Significant suppression in di-jet coincidence measurements!**

# Di-jet azimuthal correlation in Cu+Cu




| Centrality | Width |
|---|---|
| 0–20% | $0.223 \pm 0.017$ |
| 20–40% | $0.231 \pm 0.016$ |
| 40–60% | $0.260 \pm 0.059$ |
| 60–80% | $0.253 \pm 0.055$ |

**Small $k_T$ broadening of surviving parton in Cu+Cu**

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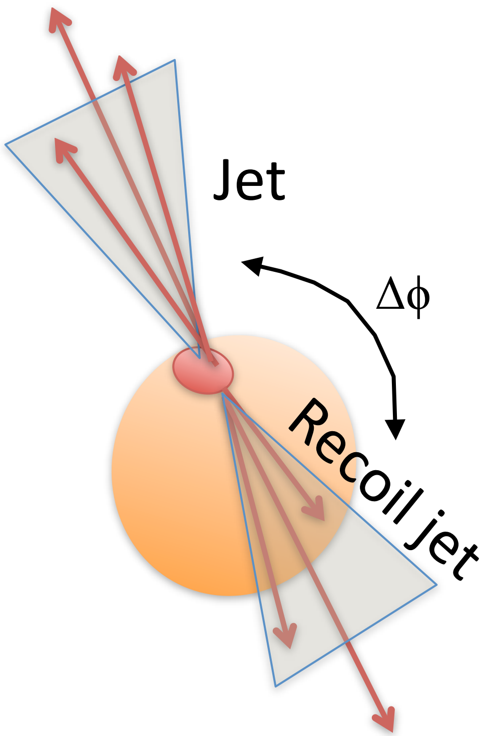


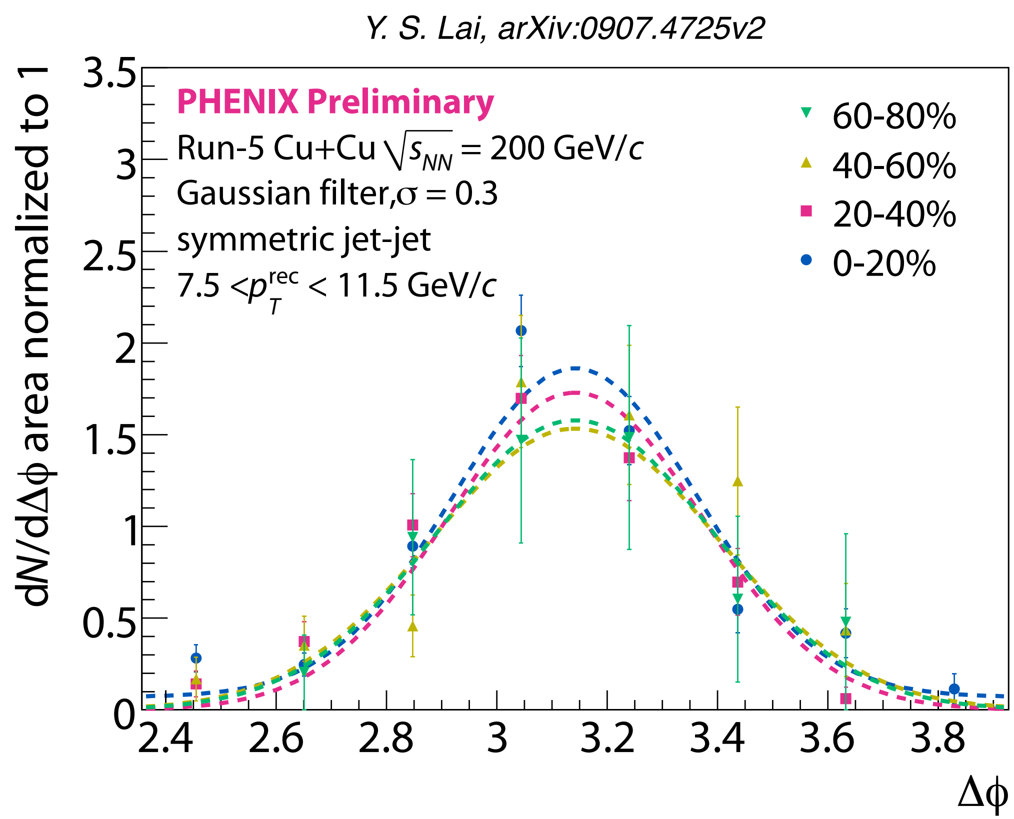


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**Small $k_T$ broadening of surviving parton in Cu+Cu**

**Are we biasing our (di-)jet measurements towards non-interacting jets? Or is our HI jet energy underestimated due to jet broadening!?**

**Can we test this with an *independent* measurement!?**

# Can we test our (potential) jet-finding biases with an independent measurement ?

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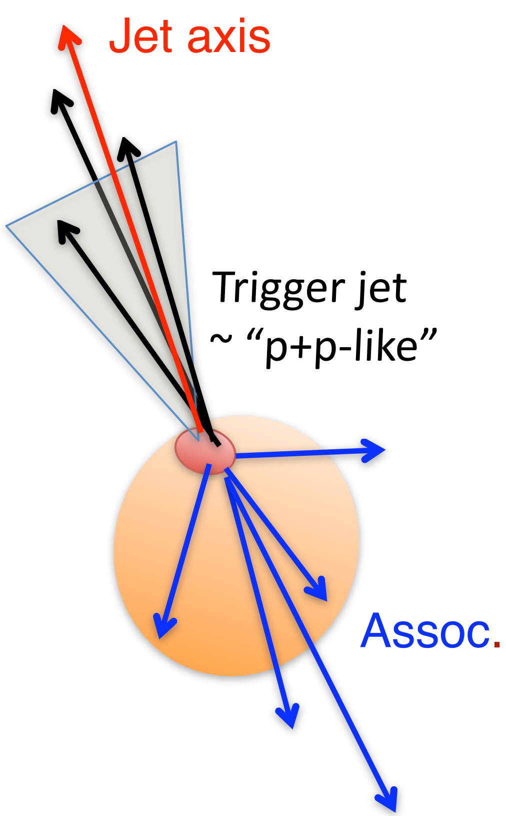
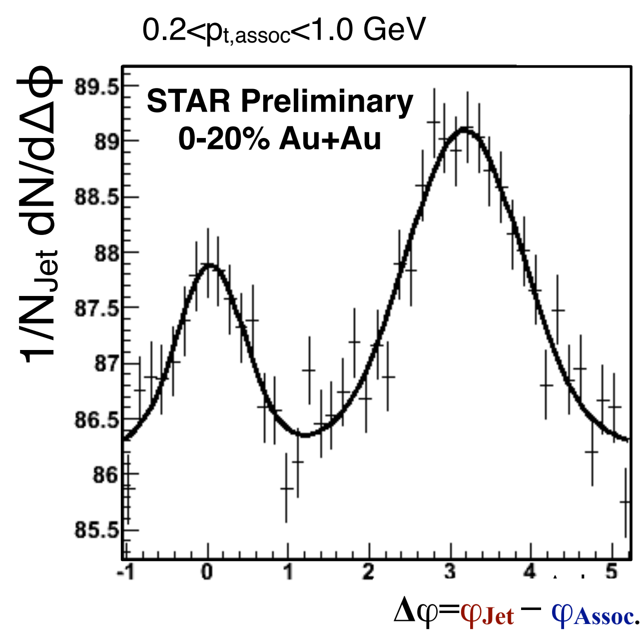
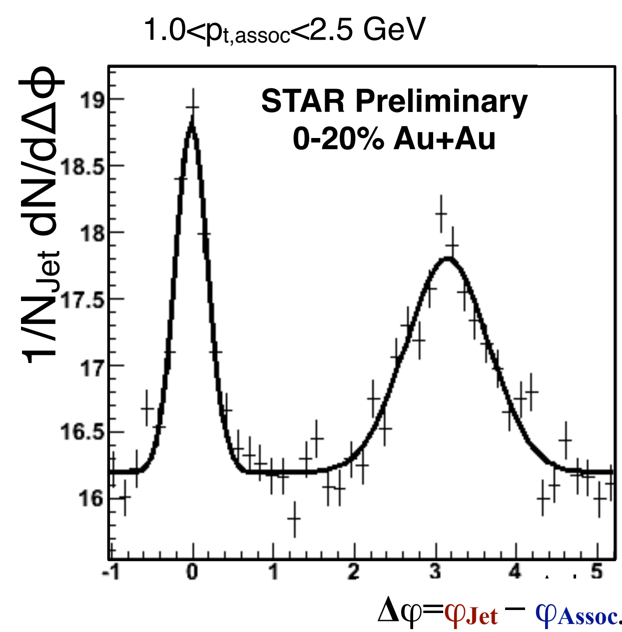
## Yes, utilize Jet-Hadron correlations (JH)!



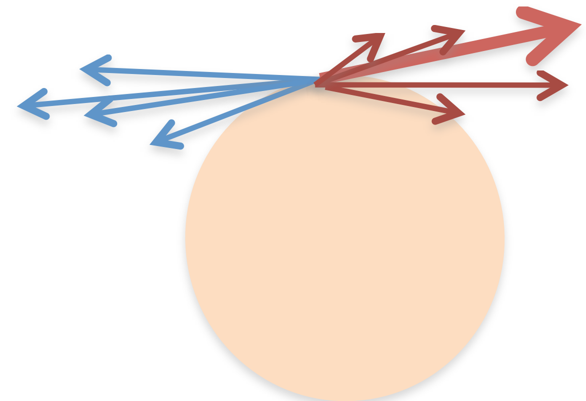

**Increased kinematics in JH due to jet requirement!**

***Different systematics*** **in bkg. correction compared to full-jet measurements!**

# The two scenarios ...

## If tangential (halo) emission:

→ Away side yield in Au+Au similar to p+p, also for low $p_{T,assoc}$

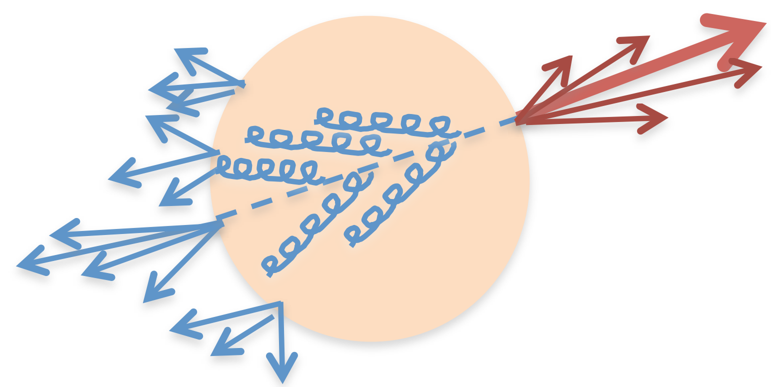


## If energy loss:

→ Decrease of high-$p_{T,assoc}$ particles

→ Strong enhancement of low $p_{T,assoc}$

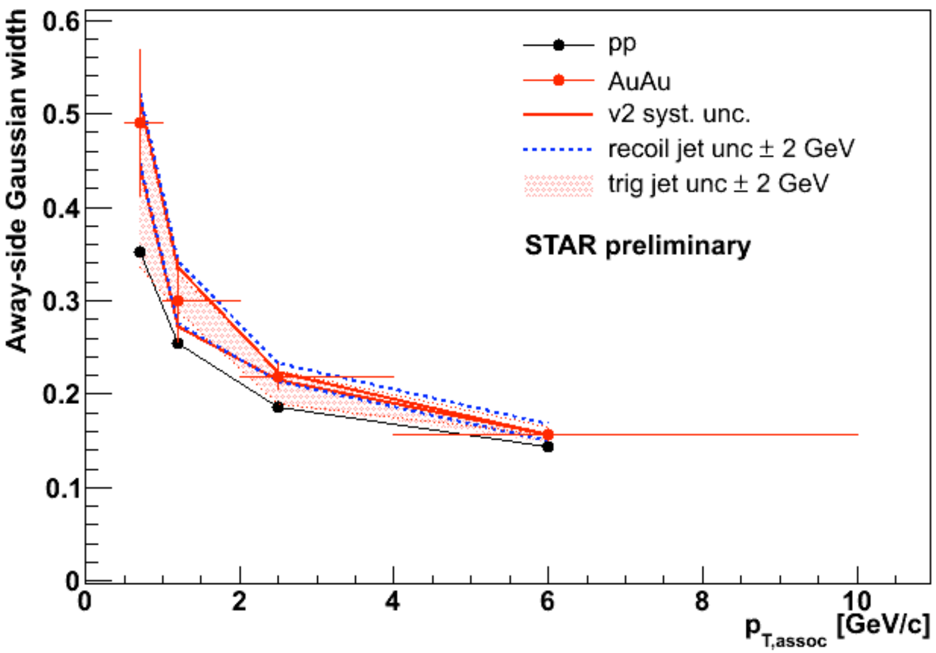
→ Broadening



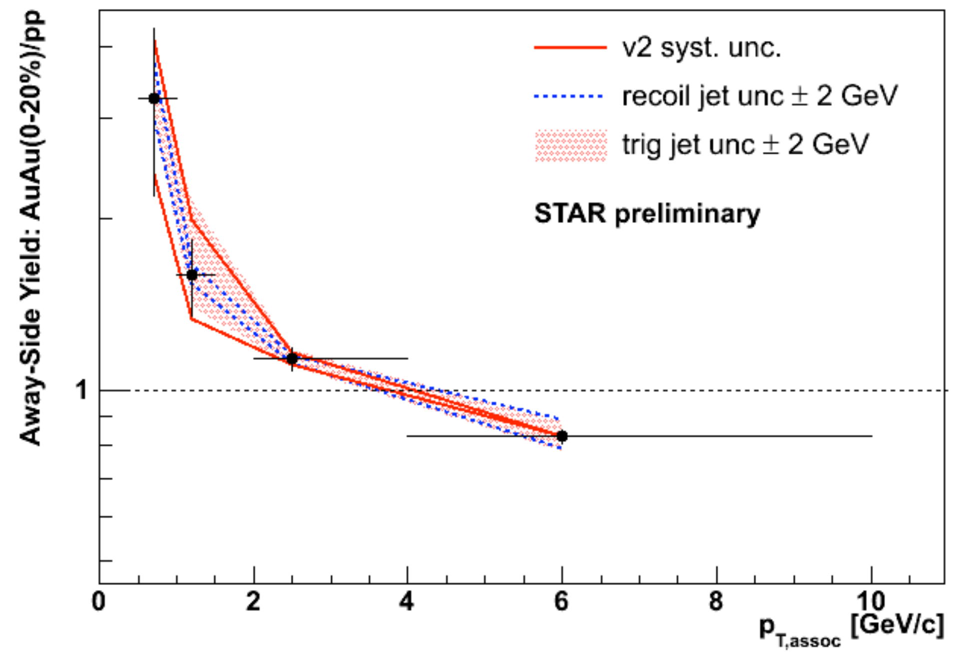
# “Jet-finding bias” assessment via jet-hadron correlations

**Measure jet-hadron correlations with the requirement of a fully reconstruct recoil jet:**

Away-side width




Away-side $I_{AA}$



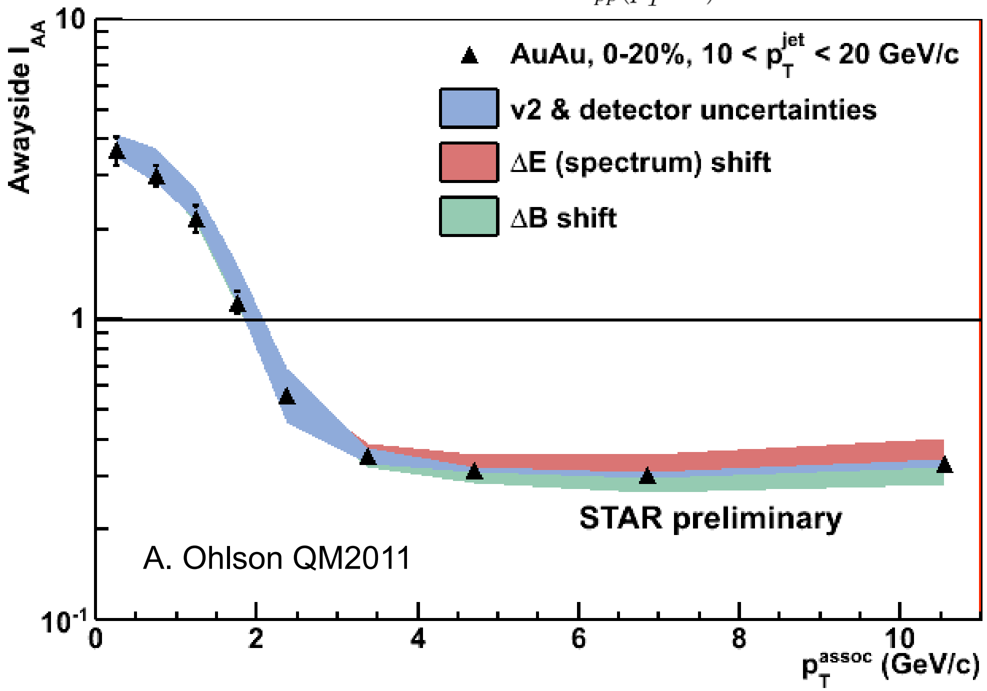

**Away-side shows broadening and softening in jet-hadron correlations**

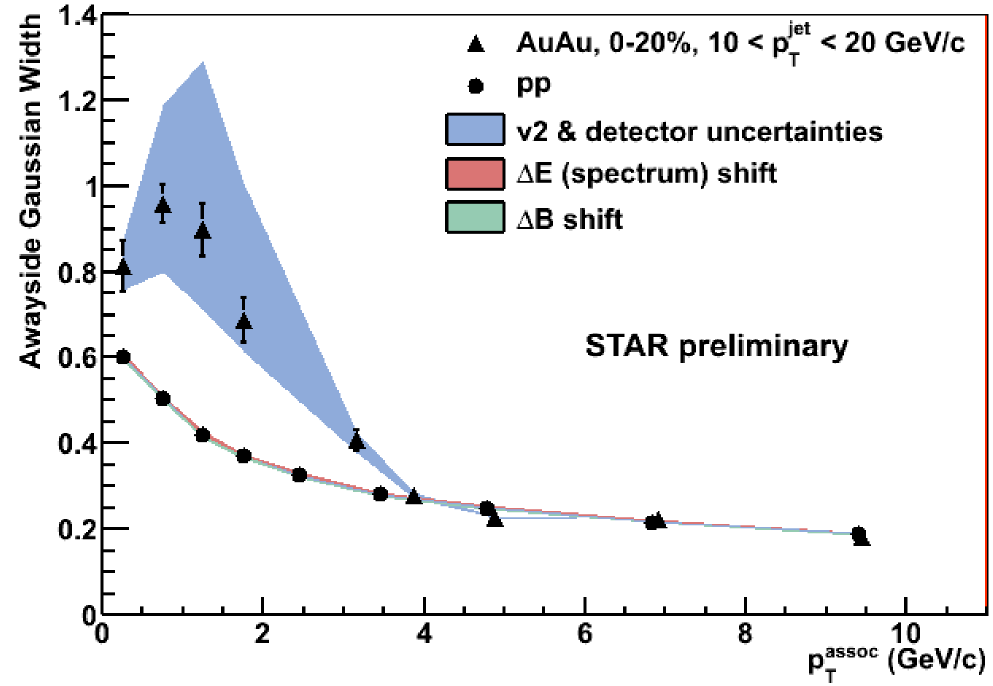
**⇒ Highly biased jets ($p_T^{Cut}$>2 GeV) seem to be modified;
jet-finding algorithm not only reconstructing unmodified jet!**

**⇒ Suppression of di-jet coincidence most likely due to “out-of-cone energy”**

# JH: Away-side width and $I_{AA}$

$$I_{AA}(p_T^{assoc}) = \frac{Y_{AA}(p_T^{assoc})}{Y_{pp}(p_T^{assoc})}$$



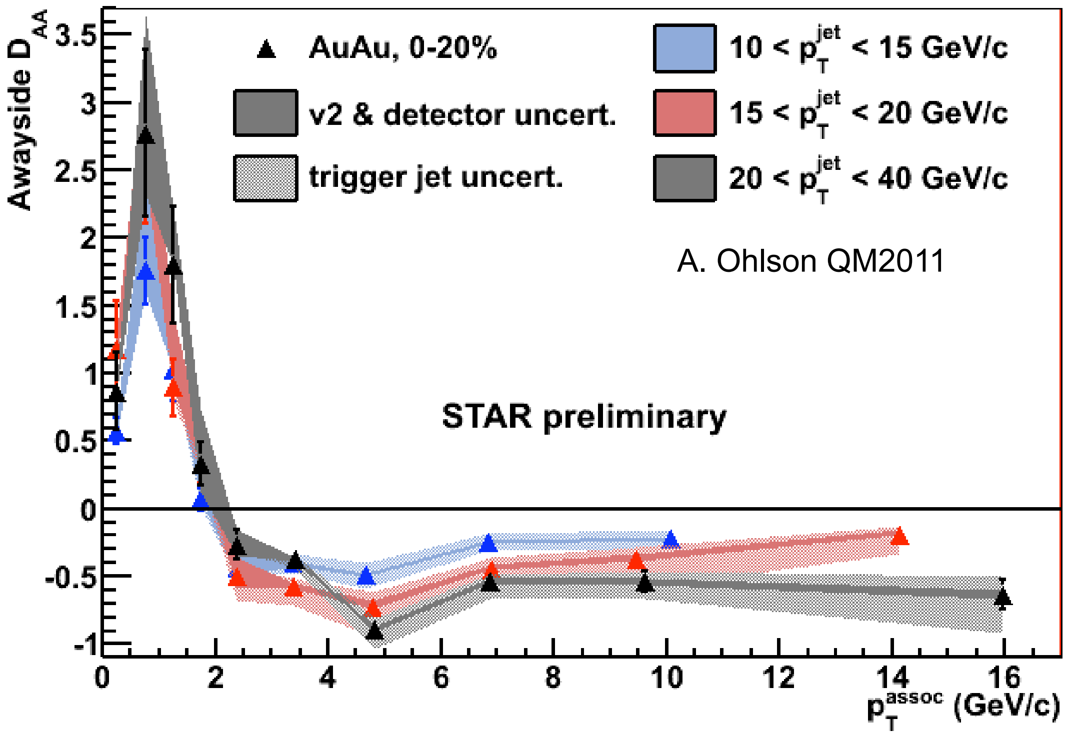




- Significant (gaussian) jet broadening for recoil jets
- Softening of jet “fragmentation”:
  suppression at high pT and enhancement at low pT (pT<2 GeV)
- Measurements/conclusions robust wrt to background subtraction

Further studies: jet energy scale/uncertainties on near-side (Δη study), included in systematics

# JH: Away-side $D_{AA}$ vs jet energy

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc} \qquad \Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$




| $p_T^{jet}$ (GeV/$c$) | AS $\Delta$B (GeV/$c$) |
|---|---|
| 10-15 | $1.6^{+1.5\,+0.5}_{-0.3\,-0.5}$ |
| 15-20 | $2.3^{+1.8+0.5}_{-0.5-1.3}$ |
| 20-40 | $2.5^{+2.0+0.5}_{-0.8-0.8}$ |

**Away-side yields enhancement/suppression not fully balanced, more energy at low $p_T$ in Au+Au**

**<u>But</u> significant amount of energy at low $p_T$ compensated by high-$p_T$ suppression!**

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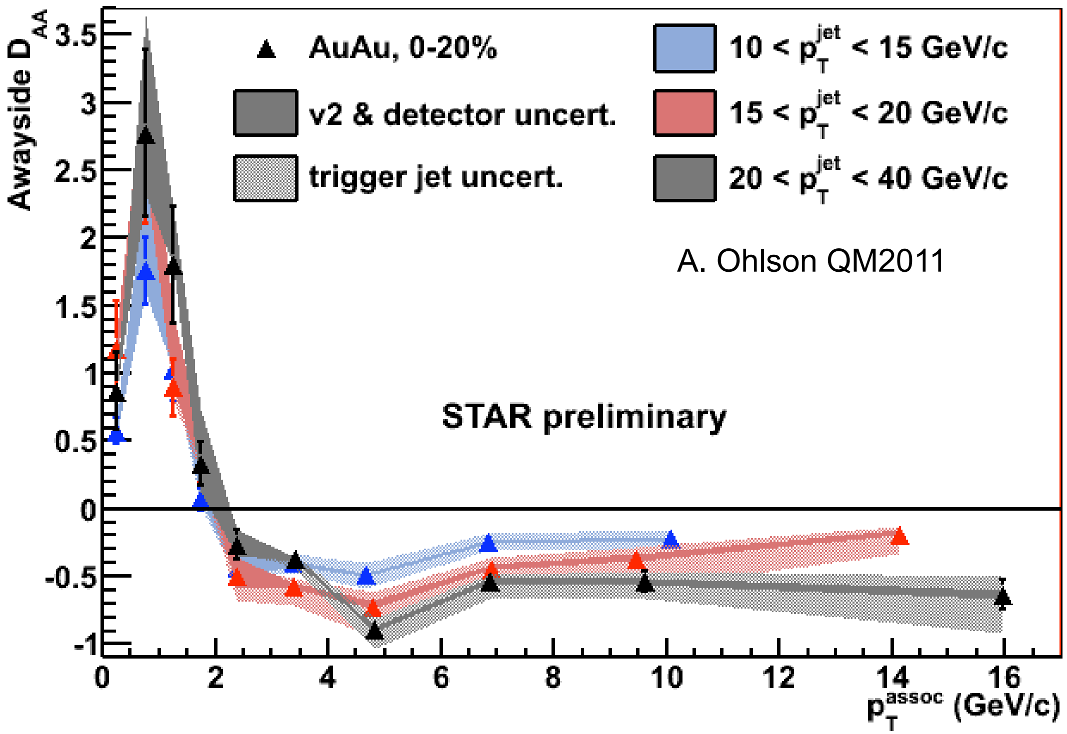


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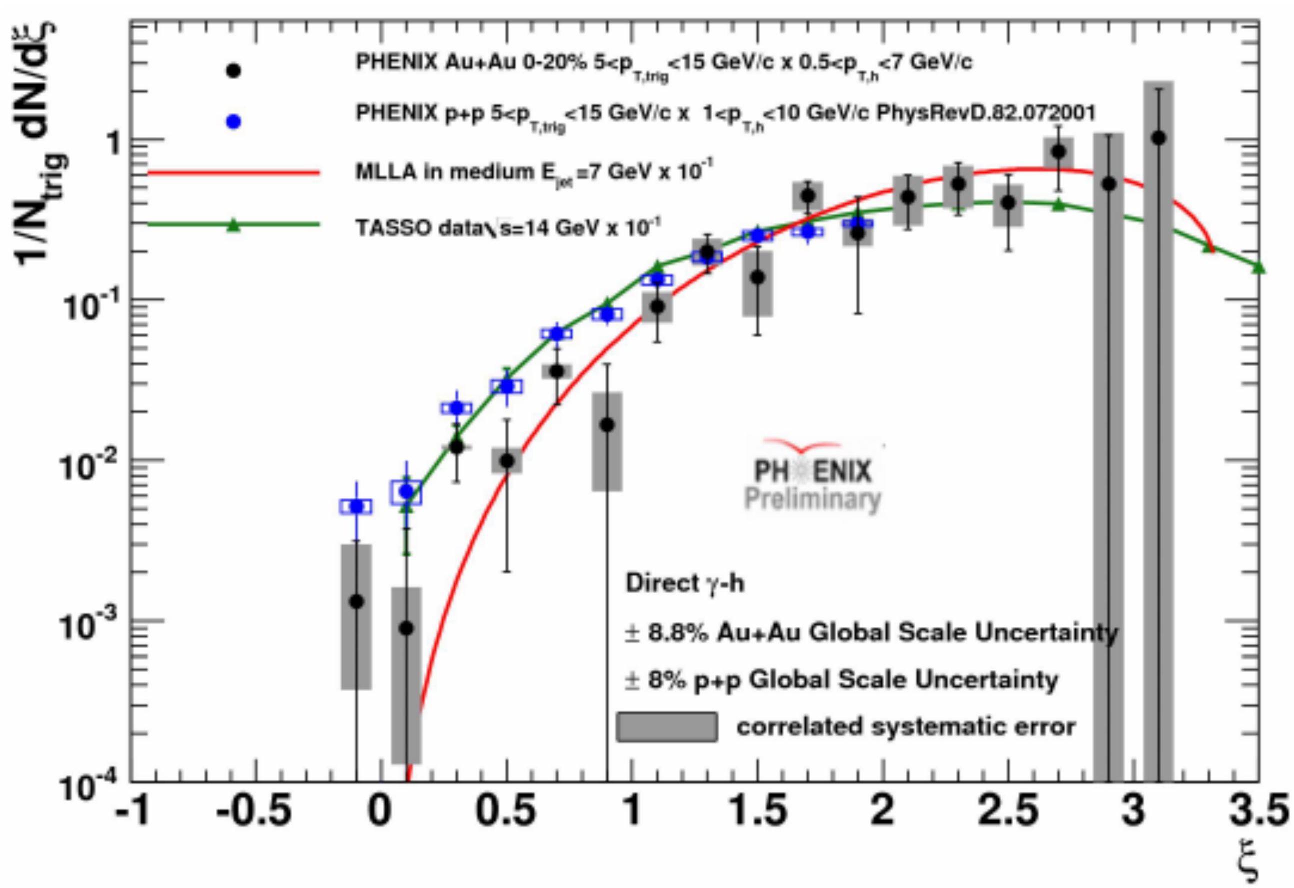
**Jet-quenching at work !**

# Direct γ-hadron correlations

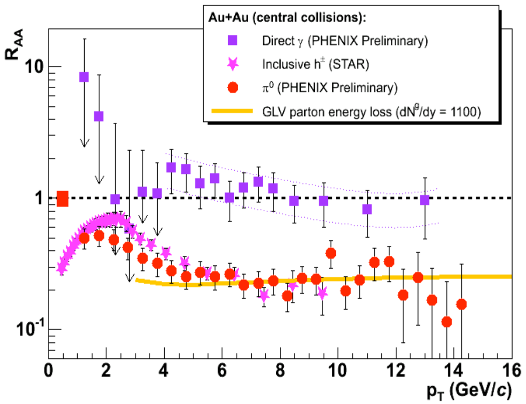


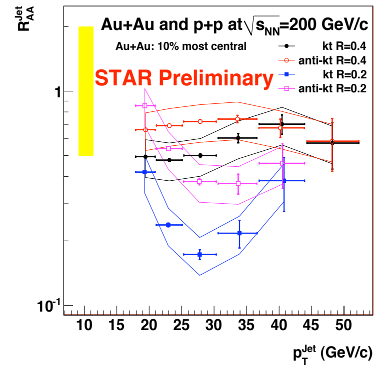

Tasso:
Braunschweig et al. , Z. Phys. 320 C47, 187
MLA:
Borghini, Wiedemann, hep-ph/0506218

$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

**Softening of jet fragmentation measured in γ-jets!**

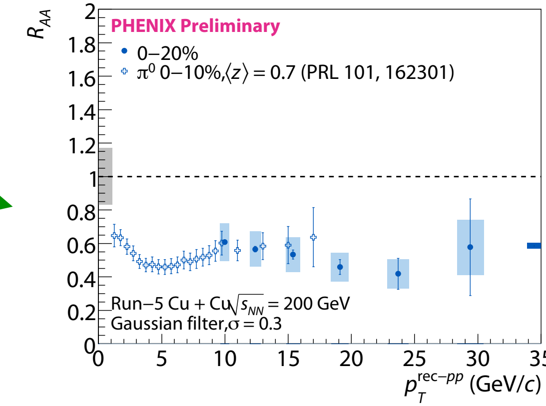
# Summary @ RHIC:

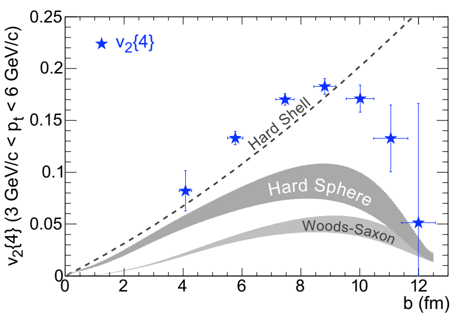



(?)

Algorithmic differences

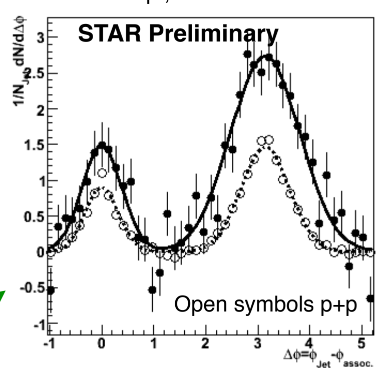


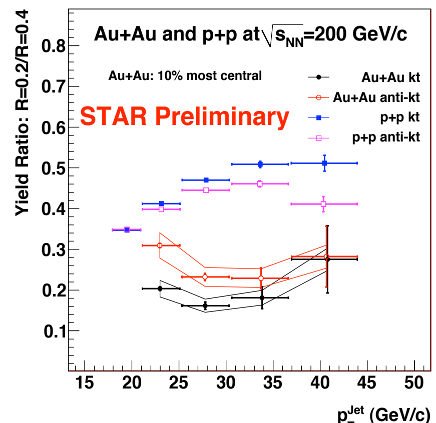



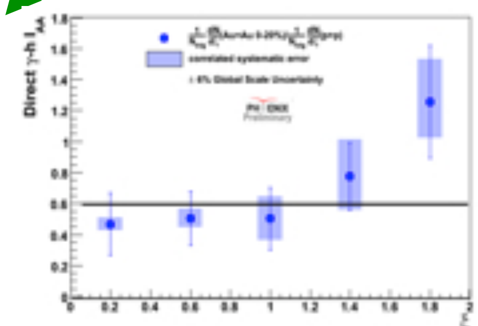

Utilize jet-finding as a tool to investigate jet v2 and non-flow

(?)

0.2<pt,assoc<1.0 GeV



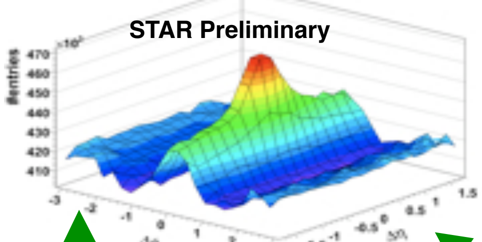



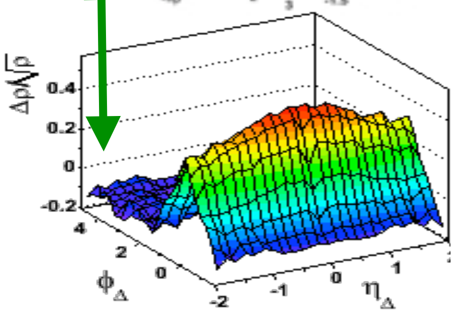



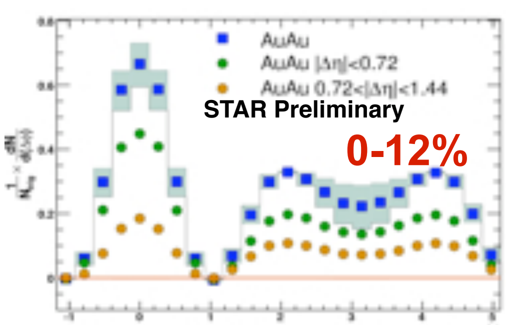
(?)

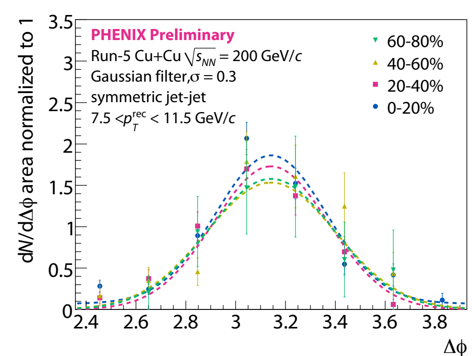
At low pT, we are measuring bulk effects (v3)!
Effect of vn at hight pT/Jets?
To be quantified!

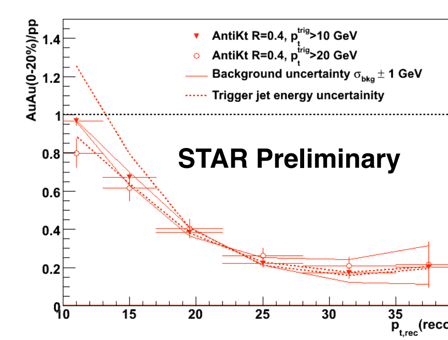
(?)



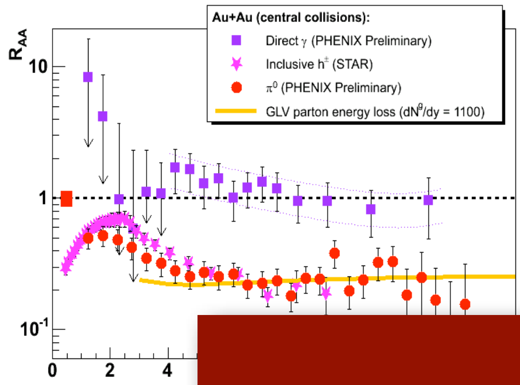



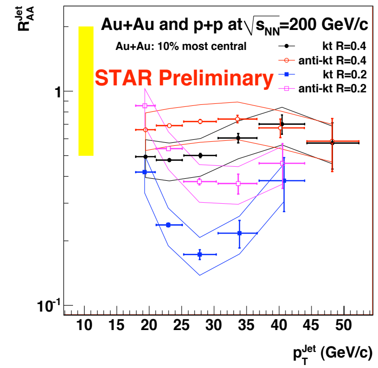



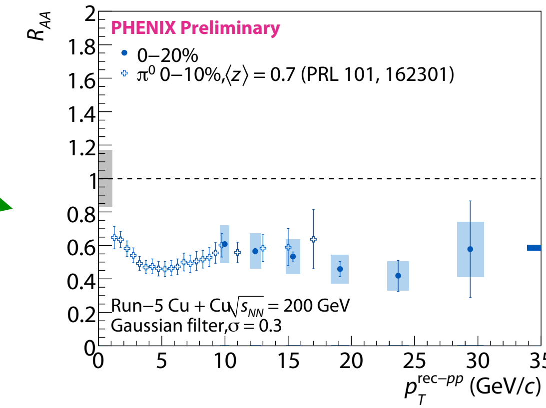
# Summary @ RHIC:

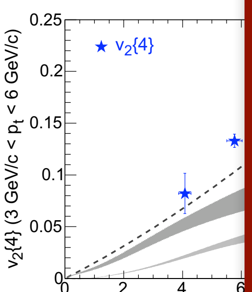


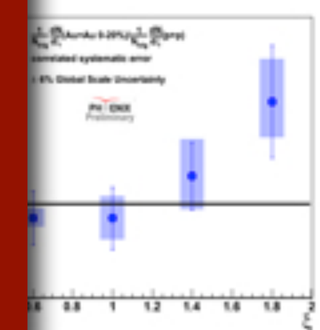




(?)

Algorithmic differences

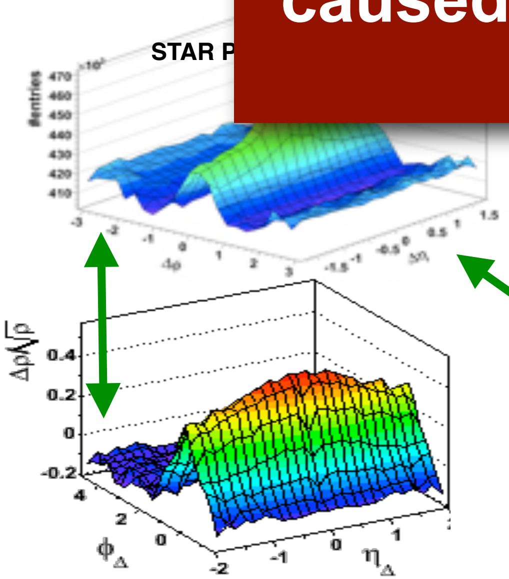


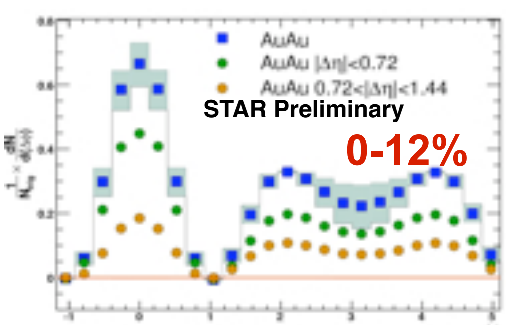
## Jet quenching @ RHIC:

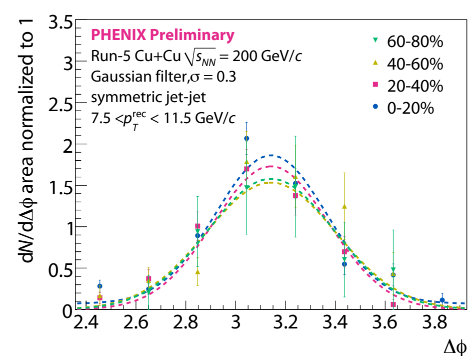
**(Light flavor) Jet quenching measurements at RHIC (mid-rapidity) can be *qualitatively* explained in a consistent picture by significant broadening and softening of the jet structure caused by (pQCD-like) partonic energy loss in the medium!**

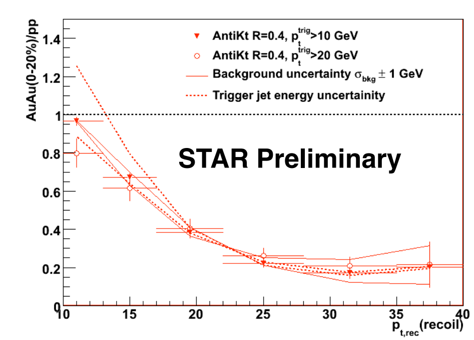



hight pT/Jets?

To be quantified!



# Just a reminder: LHC, the hard probes factory!

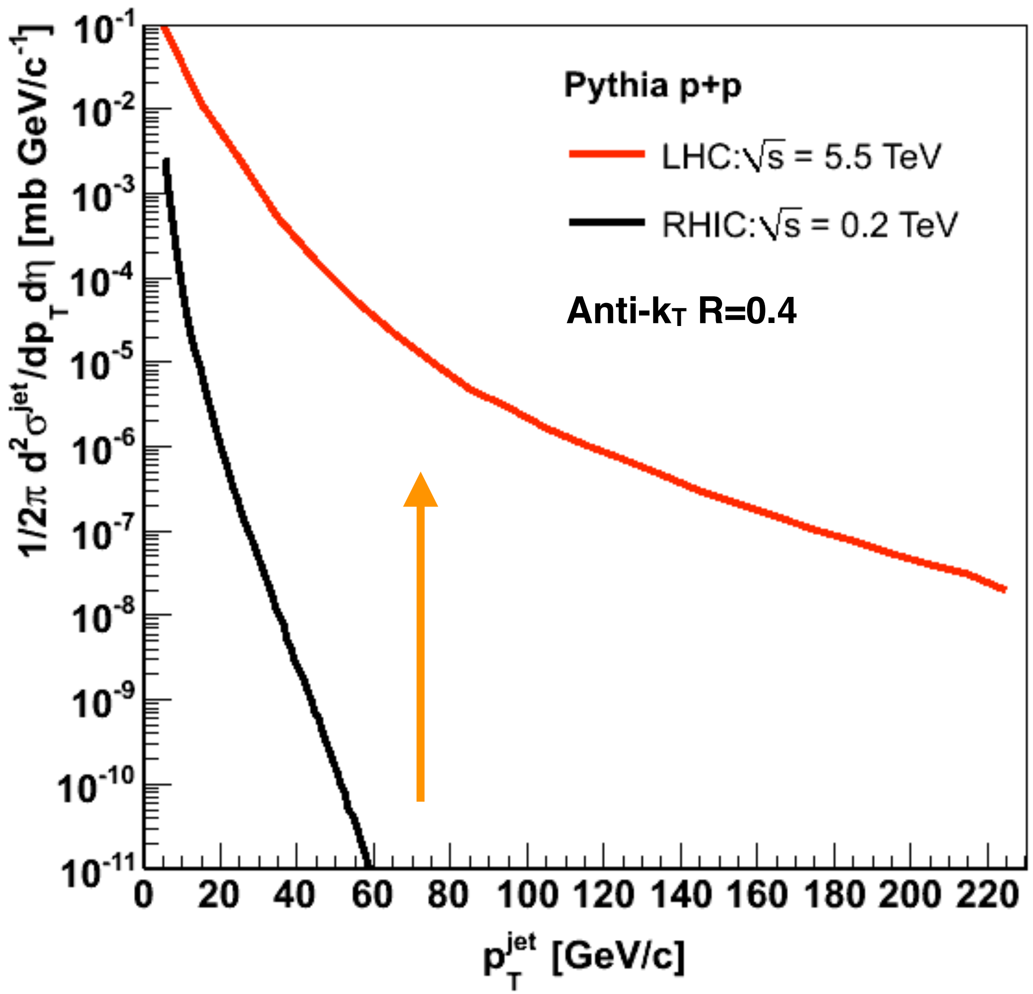
**<u>The QGP at the LHC:</u>**

*ALICE arXiv:1012.4035, arXiv:1011.3914, arXiv:1011.3916*

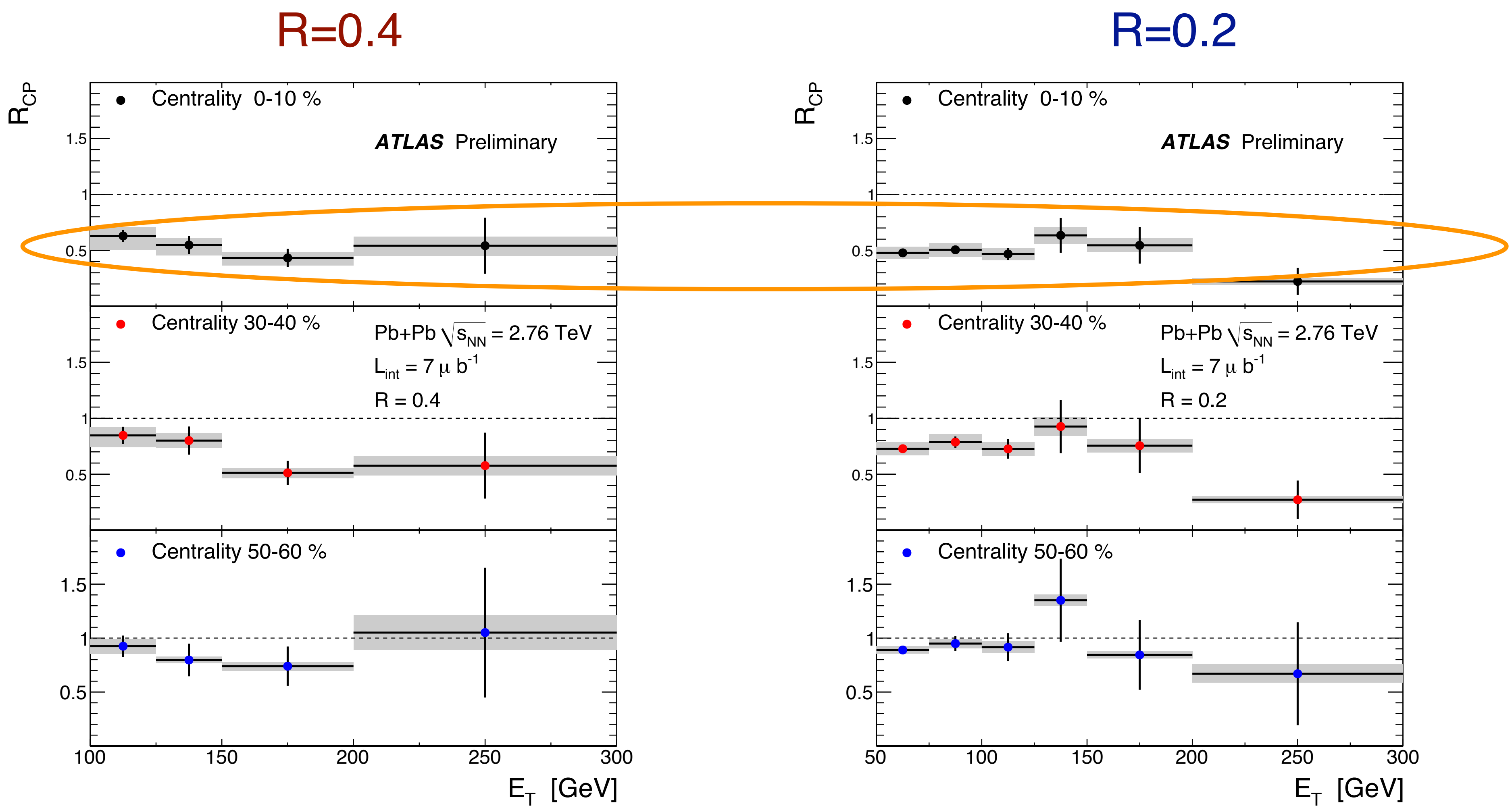
• fireball hotter and denser, lifetime longer than at RHIC

• dynamics dominated by partonic degrees of freedom

**Huge increase in yield of hard probes/jet production!**



# Jet $R_{CP}$ at the LHC



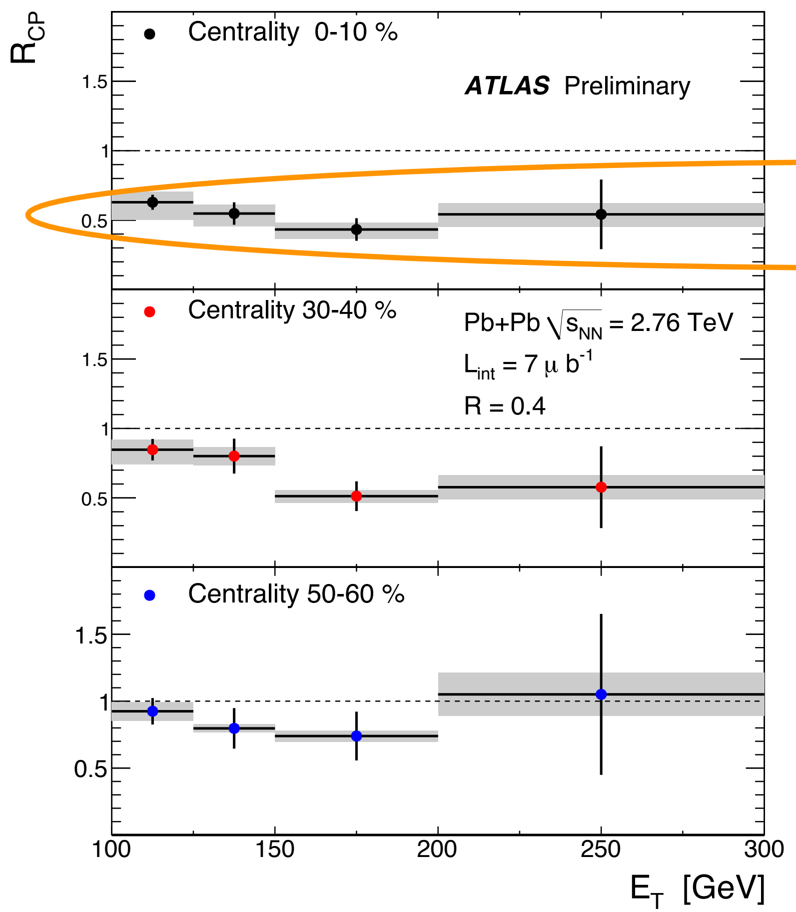

$R_{CP}^{Jet}$~ $R_{AA}$ ~ 0.5 (>50 GeV)→ jet quenching !

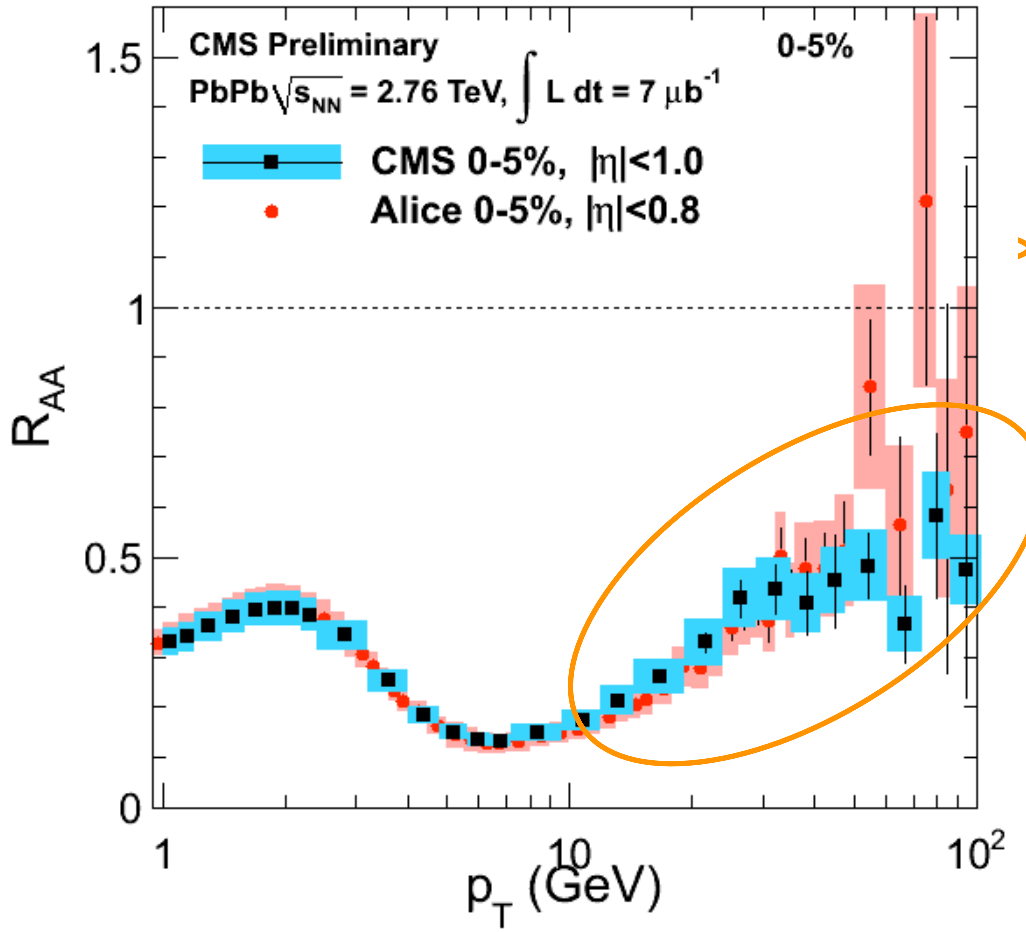
**No significant $E_T$ dependence of $R_{CP}$ for $E_T$>100 GeV**

**Similar $R_{CP}$ suppression for R=0.2 and R=0.4!**

# Jet $R_{CP}$ at the LHC

R=0.4



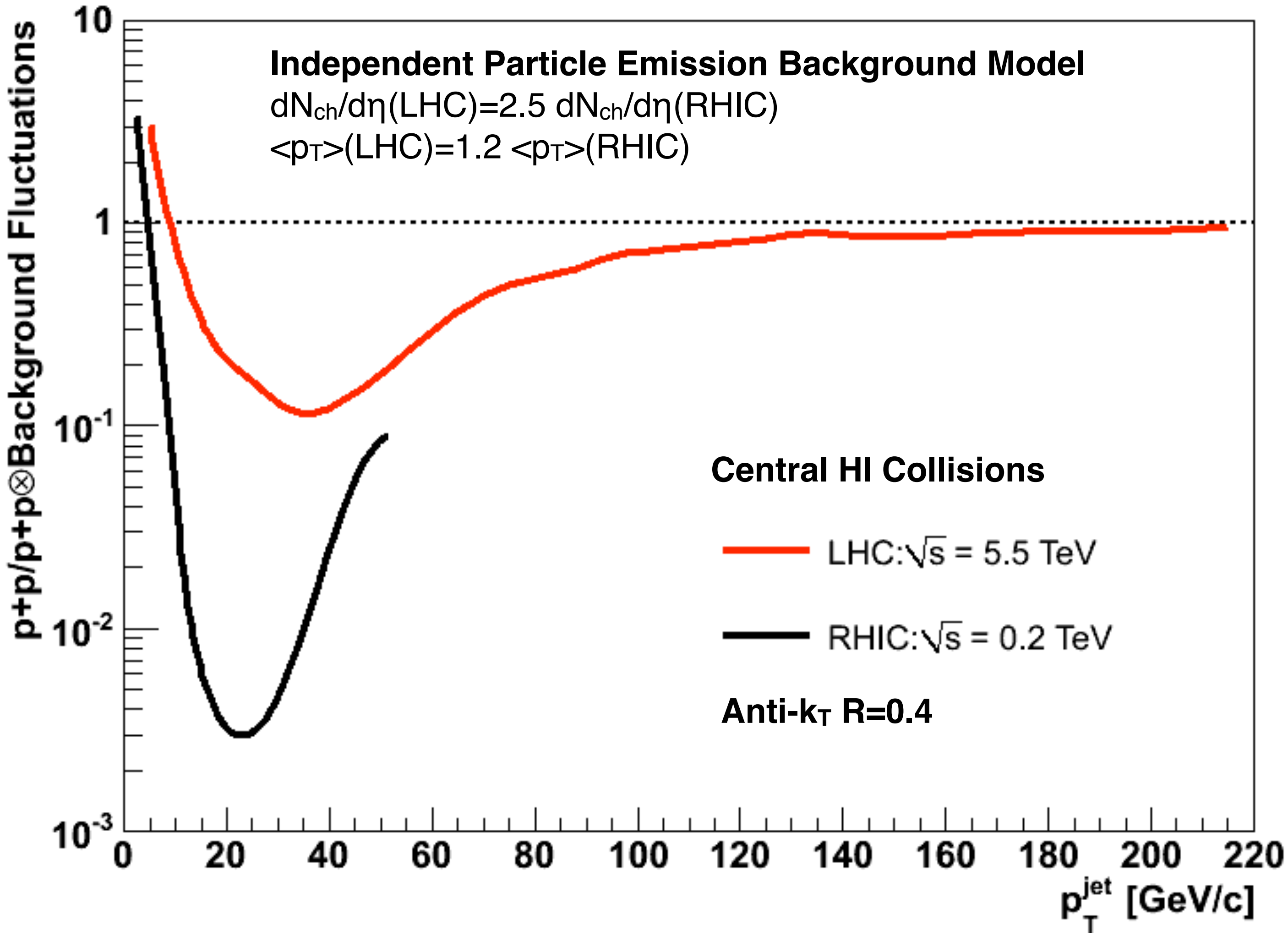

$R_{CP}^{Jet}$~ $R_{AA}$ ~ 0.5 (>50 GeV)→ jet quenching !

No significant $E_T$ dependence of $R_{CP}$ for $E_T$>100 GeV

Similar $R_{CP}$ suppression for R=0.2 and R=0.4!

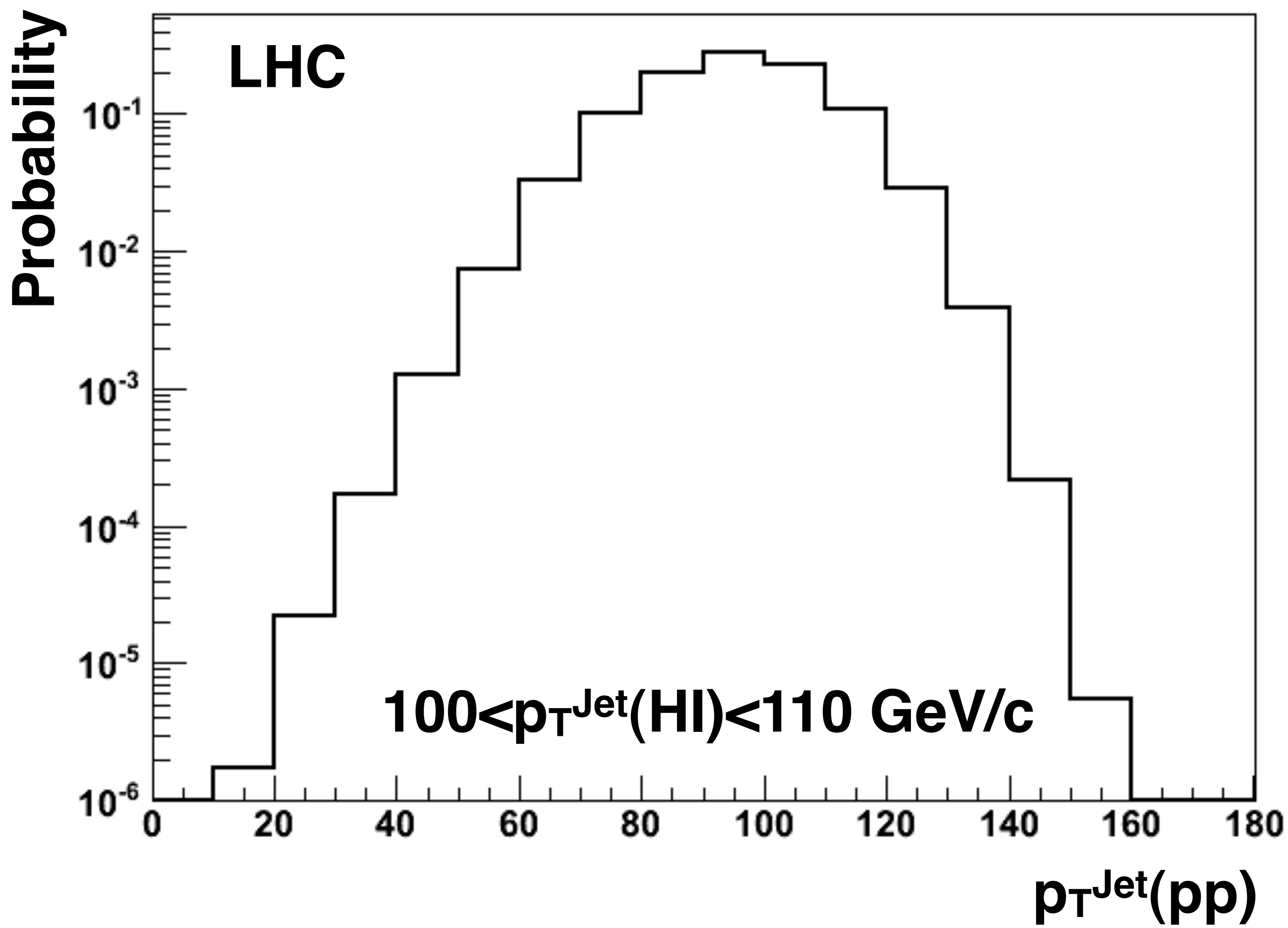
# Reminder: Effect of background fluctuations at the LHC

## Toy model: use the independent emission model and p+p x-section




**Small effect on inclusive jet x-section at the LHC for $p_T^{Jet}$>100 GeV/c**

# Effect of fluctuations on individual jet energy scale ...




Fluctuations have a visible effect on the p+p equivalent JES selection

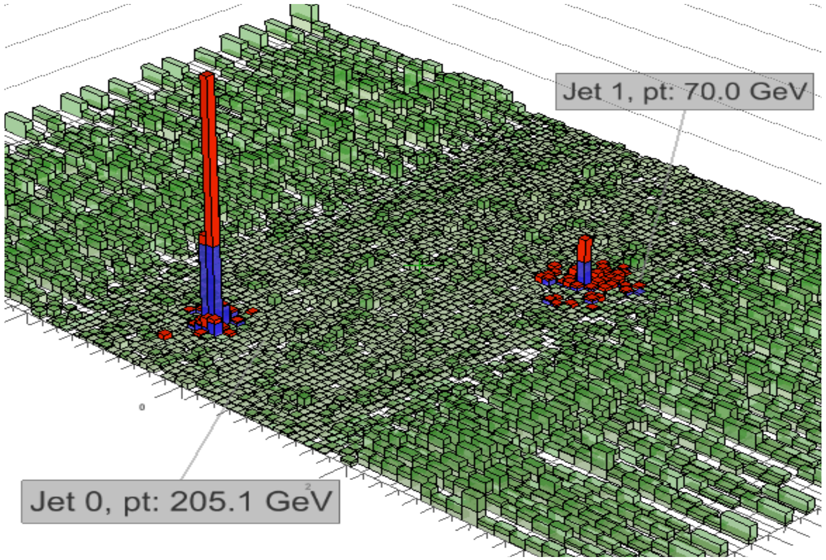
Magnitude off effect dependents on details of the fluctuation spectrum

How to take n-th hard scattering into account not fully understood yet !?
Do they have an effect !? Remember on next slide you might “trigger” on them!?

# Di-jet energy imbalance $A_j$

**Quantify energy imbalance:**

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

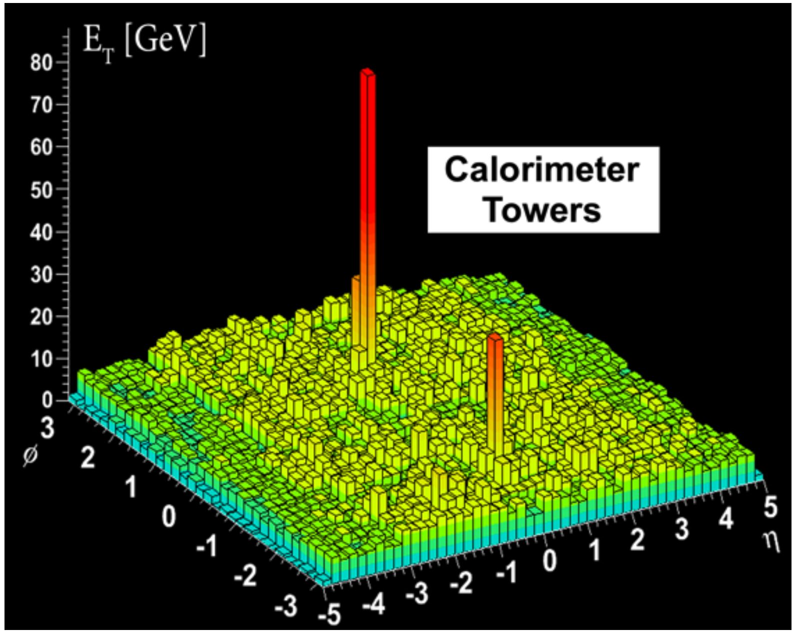



**Atlas:**

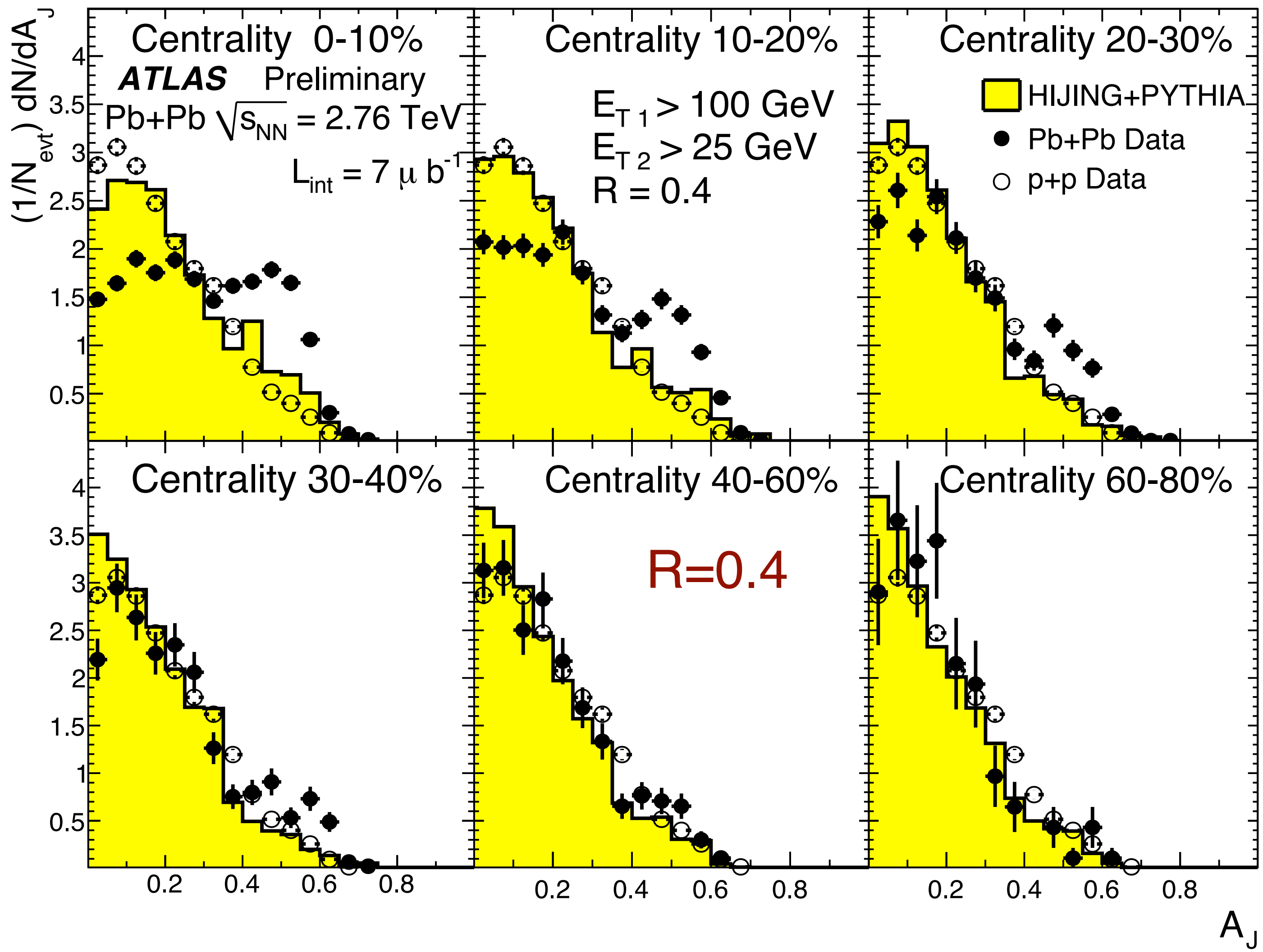
**Anti-$K_T$ R=0.4 (0.2)**

**$p_{T,1}$ > 100 GeV**

**$p_{T,2}$ > 25 GeV**

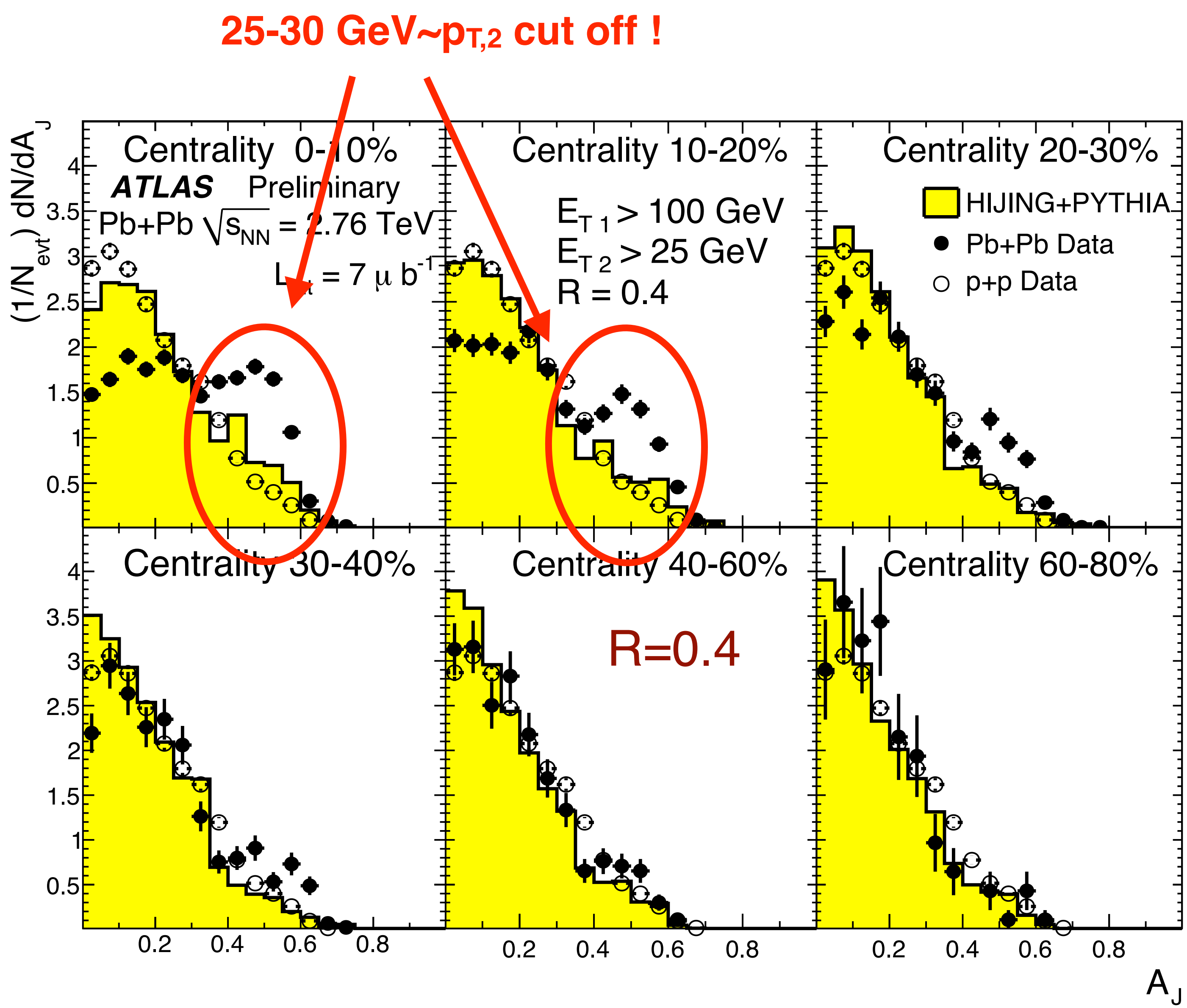


# Di-jet asymmetry measurements in ATLAS(CMS)



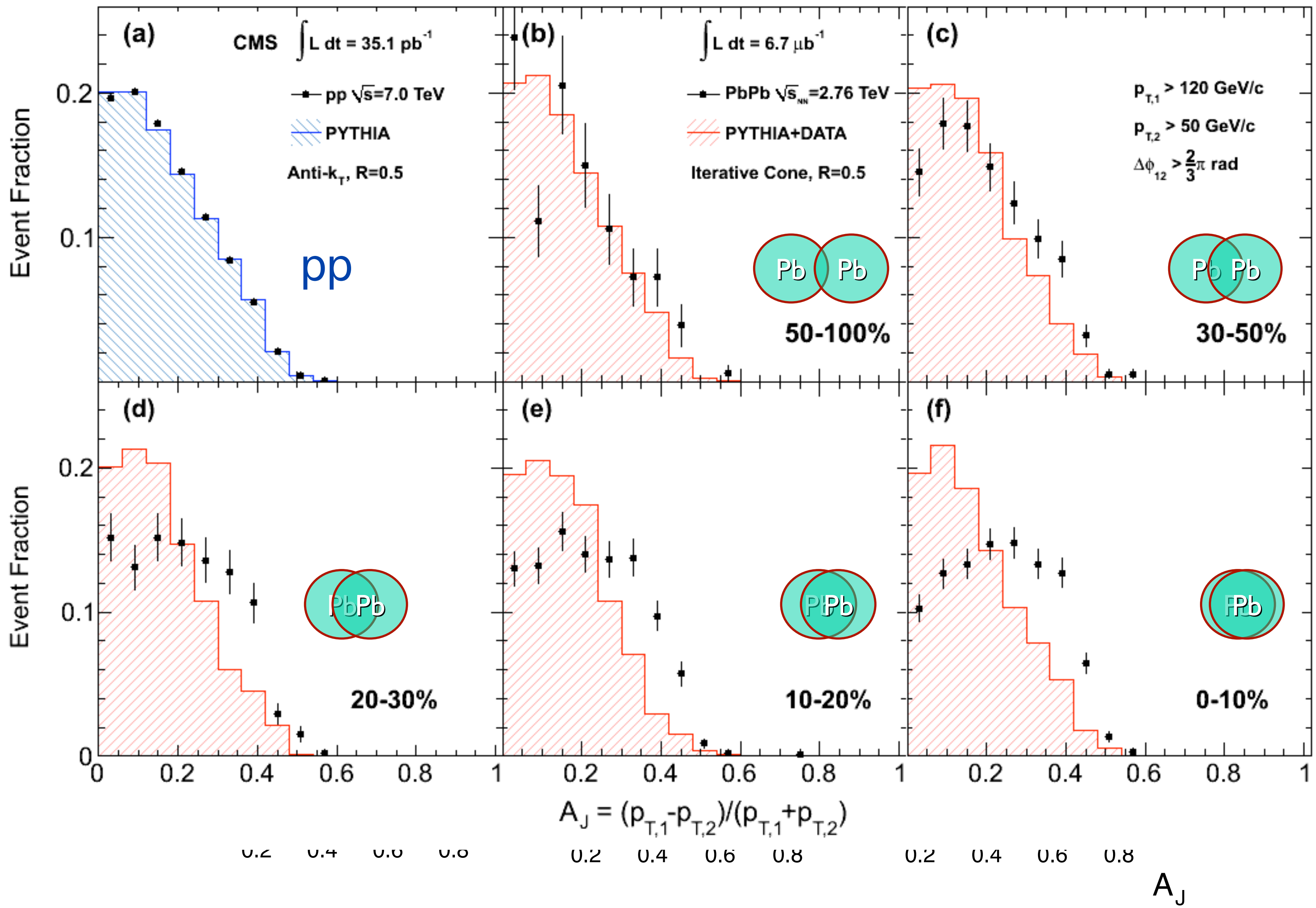

**Pronounced di-jet energy imbalance observed in central Pb+Pb**

# Di-jet asymmetry measurements in ATLAS(CMS)




**Pronounced di-jet energy imbalance observed in central Pb+Pb**

# Di-jet asymmetry measurements in ATLAS(CMS)

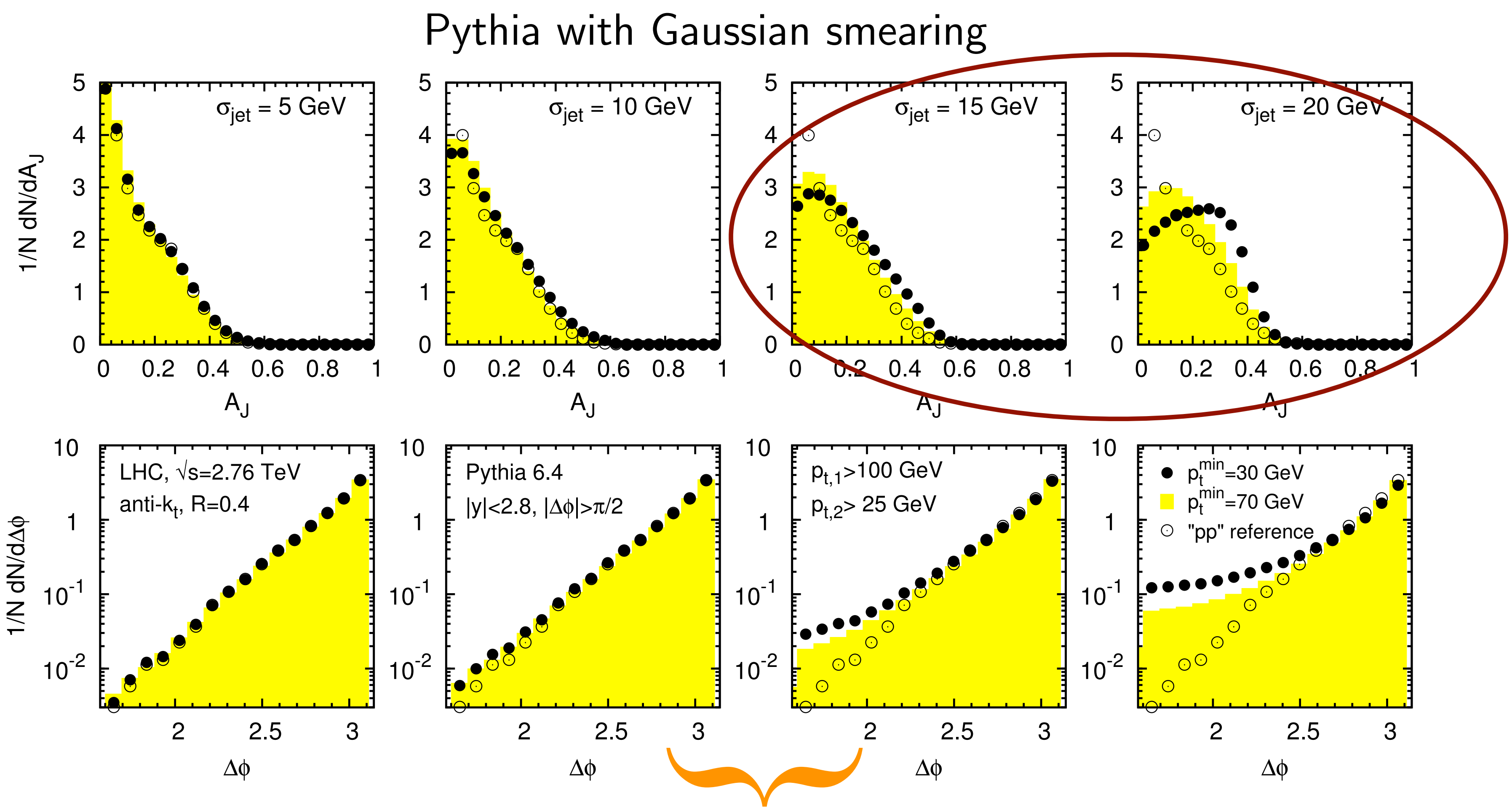



**Pronounced di-jet energy imbalance observed in central Pb+Pb**

# Di-jet asymmetry: Fluctuations (may) matter ...

*Cacciari et al, arXiv:1101.2878*

Increasing fluctuations (on trigger jet)




Estimate from independent emission as well as measured by ALICE/ATLAS

**Measurement depends on the details of the fluctuation spectrum!**

**Current background estimates suggests only small effects!**

<u>But:</u> n-th scattering, even rare, you might "trigger" on them ... (more studies needed)

# Missing $p_T^{||}$

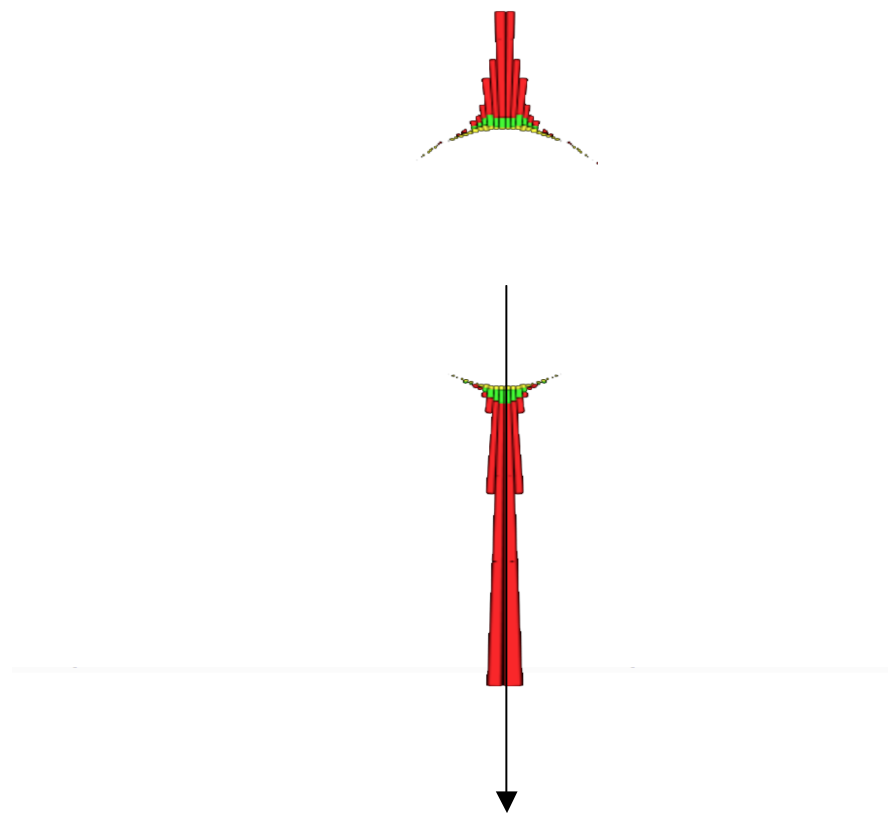
*Taken from C. Roland (CMS), QM11*

Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$ $|\eta| < 2.4$

Calculate projection of $p_T$ on leading jet axis and average over selected tracks with

$p_T > 0.5$ GeV/c and

$|\eta| < 2.4$



Leading Jet defines direction

# Missing $p_T^{||}$

*Taken from C. Roland (CMS), QM11*

Missing $p_T^{||}$: $$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$ $|\eta| < 2.4$

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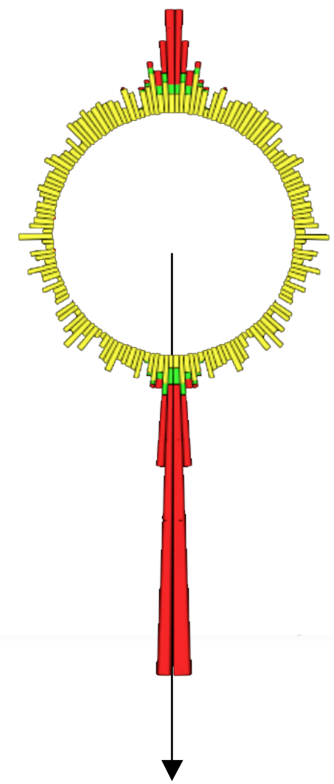


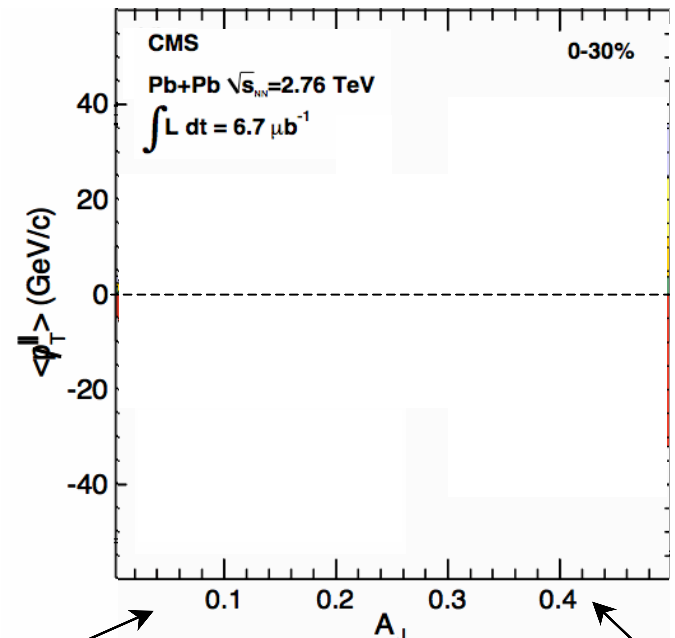
Sum all tracks in the event

# Missing $p_T^{||}$

*Taken from C. Roland (CMS), QM11*

Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$ $|\eta| < 2.4$

0-30% Central PbPb

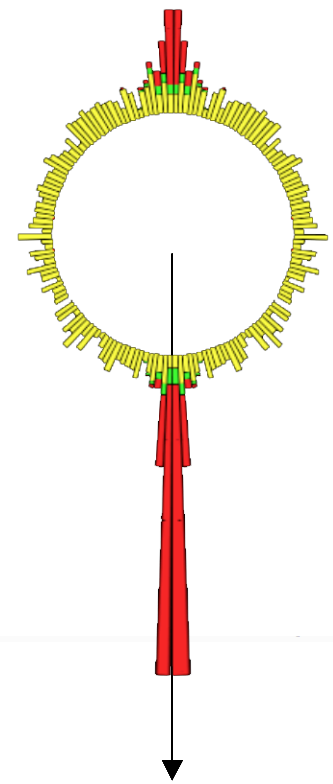



alanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



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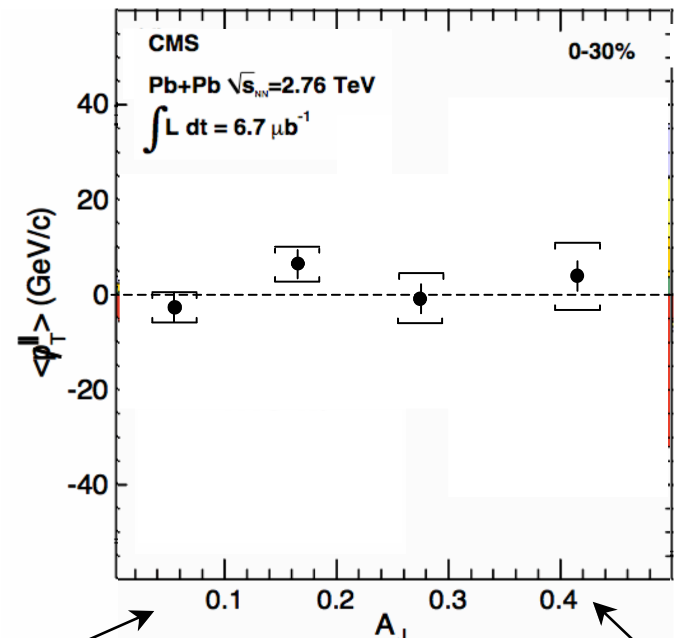
0-30% Central PbPb

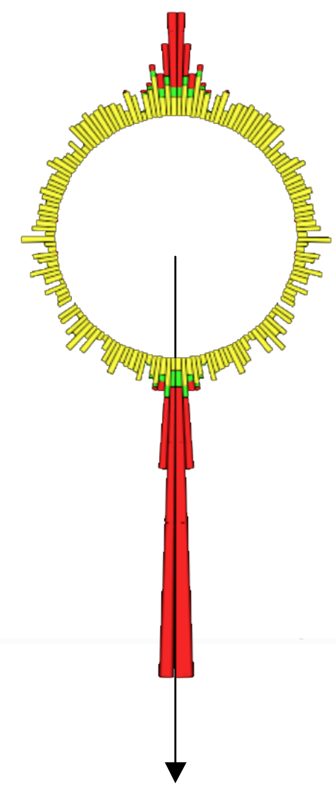



alanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



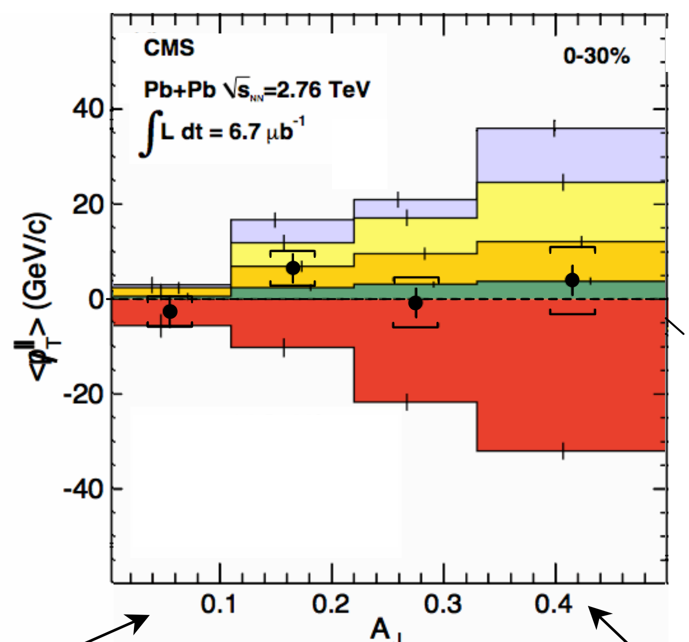
Integrating over the whole event final state the momentum balance is restored

# Missing $p_T^{\parallel}$

*Taken from C. Roland (CMS), QM11*

Missing $p_T^{\parallel}$: $\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$ $|\eta| < 2.4$

0-30% Central PbPb



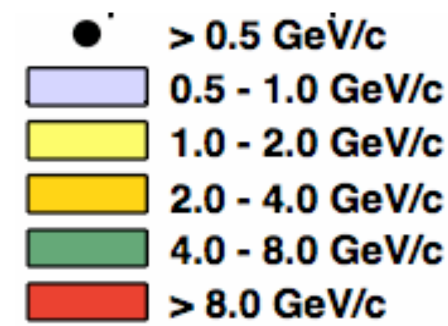

balanced jets

unbalanced jets

excess away from leading jet

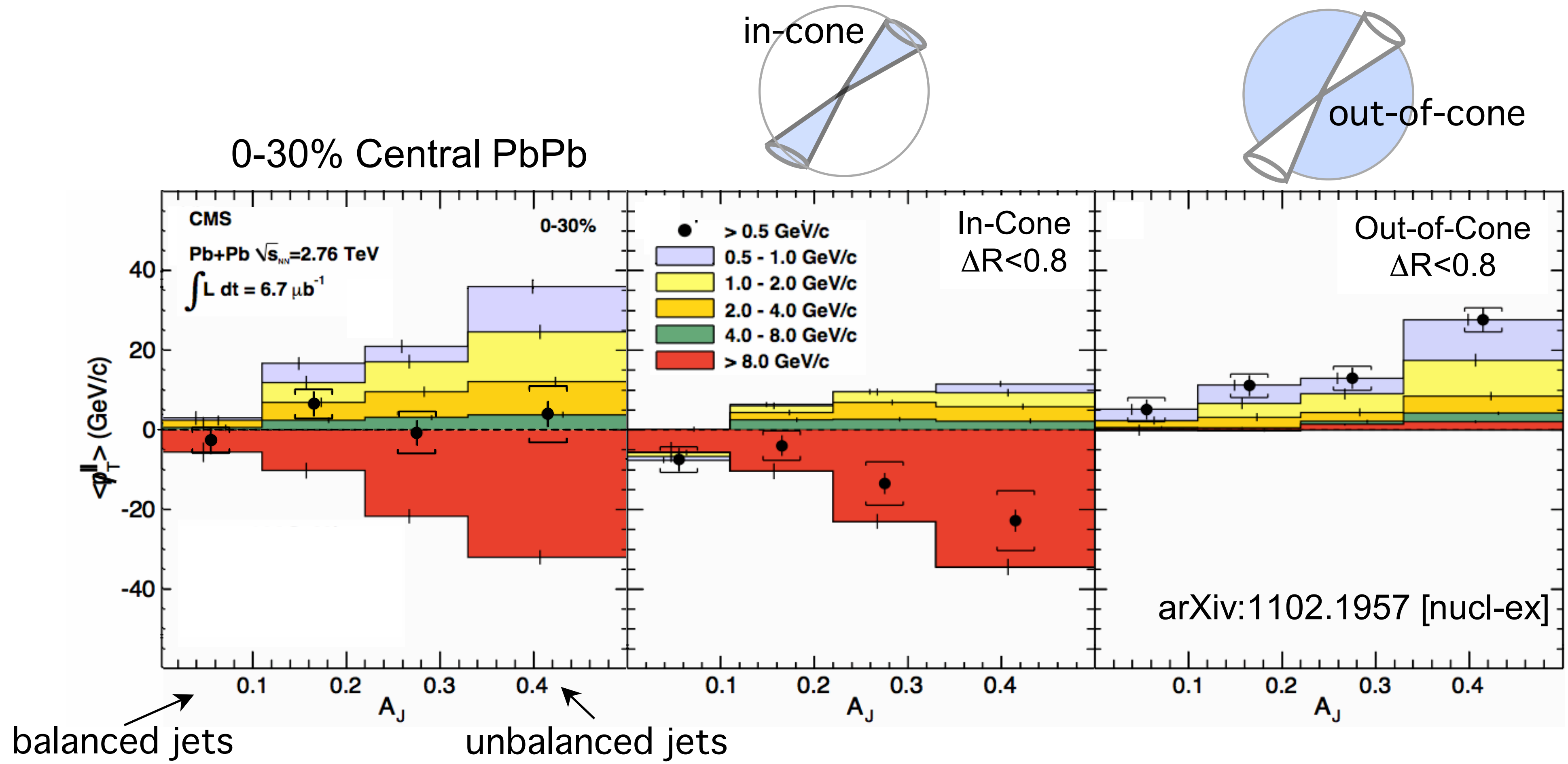
excess towards leading jet

Calculate missing $p_T$ in ranges of track $p_T$:



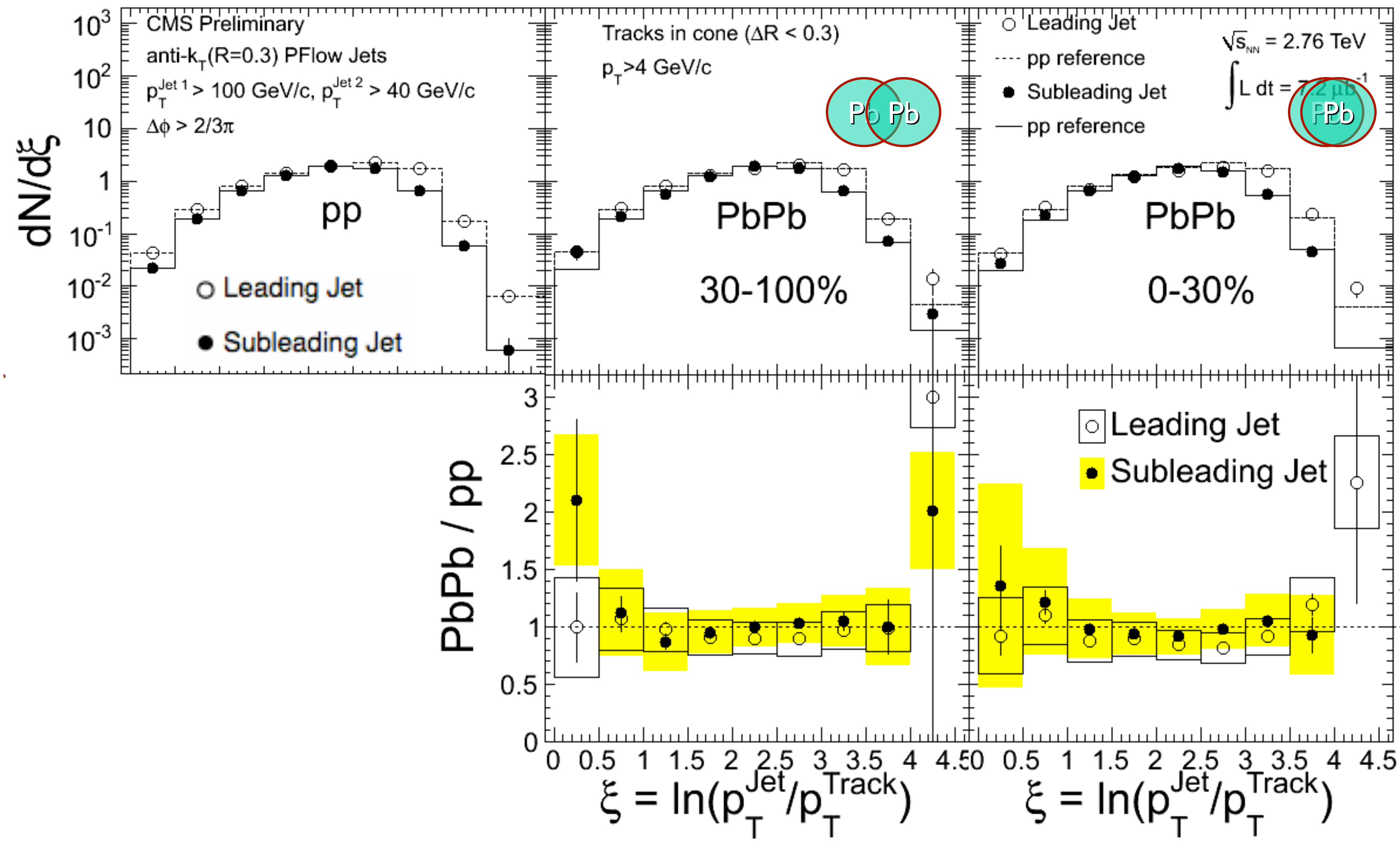

The momentum difference in the dijet is balanced by low $p_T$ particles

# Missing $p_T^{||}$ continued: Where are the low-$p_T$ particles?



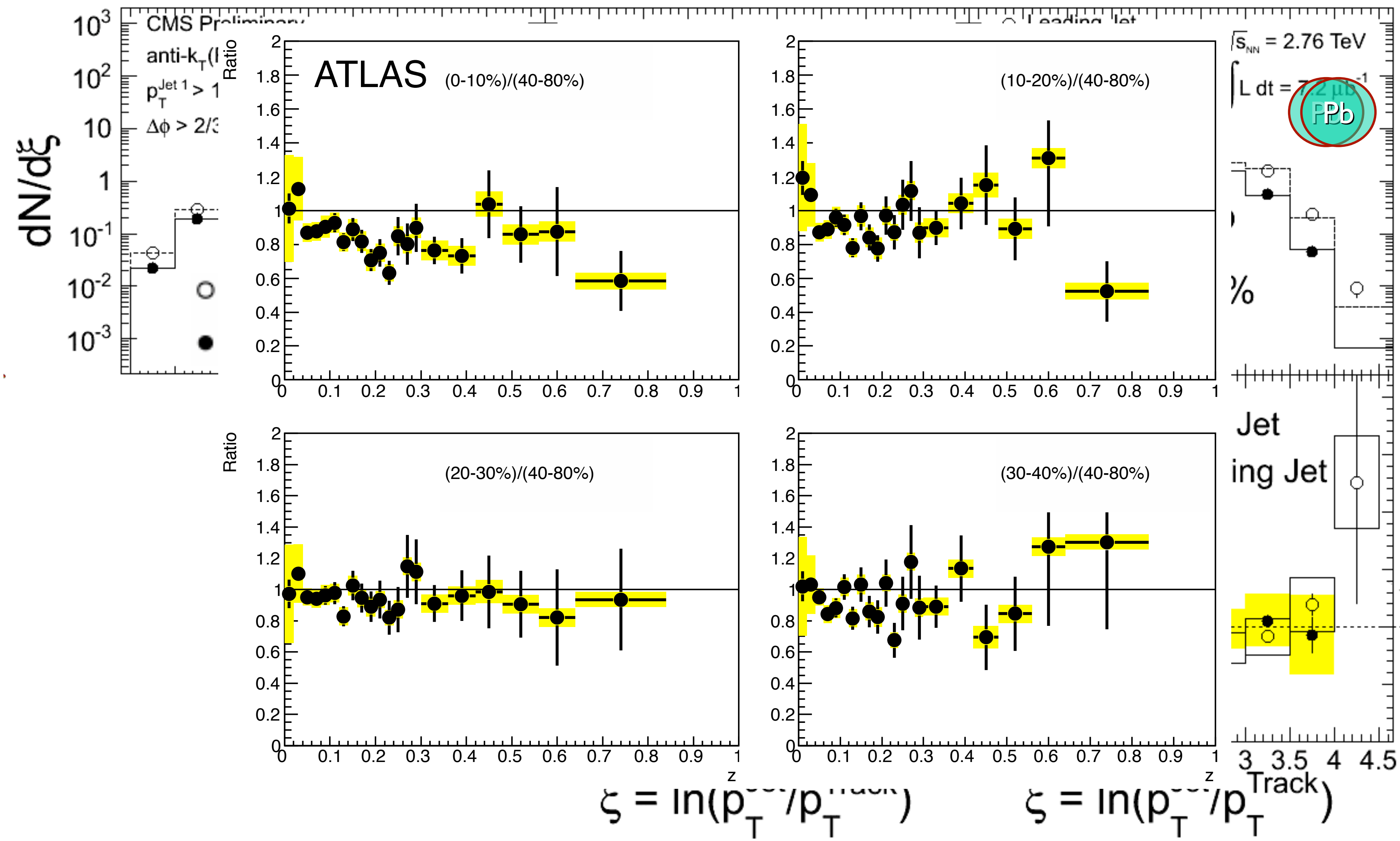

**The momentum difference in the di-jet is balanced by low $p_T$ particles at large angles relative to the away side jet axis**

# Fragmentation Functions in Pb+Pb at the LHC




**Leading and subleading jet in PbPb fragment like jets of corresponding energy in pp collisions**

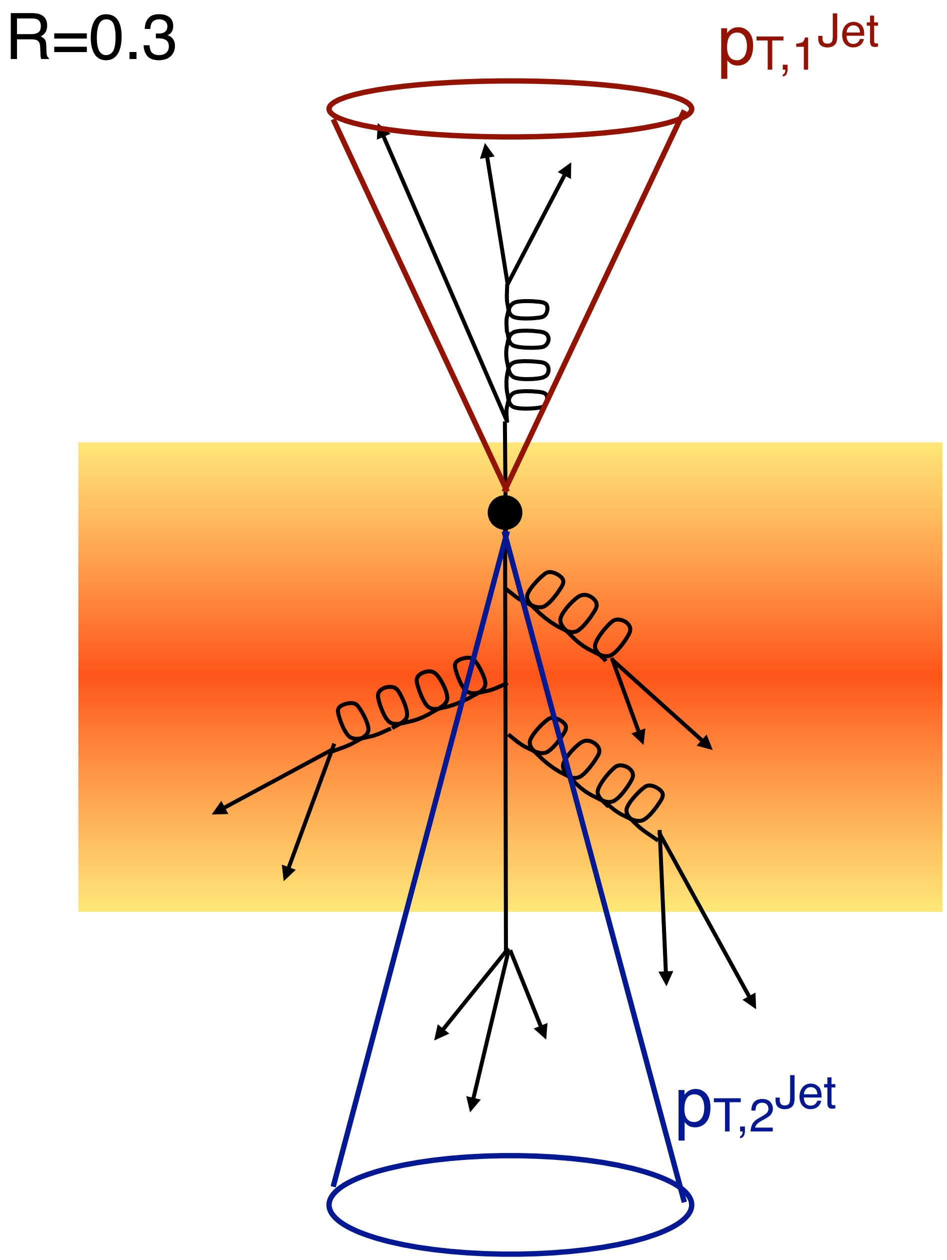
# Fragmentation Functions in Pb+Pb at the LHC




**Leading and subleading jet in PbPb fragment like jets of corresponding energy in pp collisions**

**With only a small high-z suppression (20%) ...**

# What does that mean ...




$z = p_T^{Hadron}/p_T^{Parton}$

$\xi = \ln(1/z)$

What is measured:

$z=p_T^{Track}/p_T^{Jet}$

with leading jet:

$z=p_T^{Track}/p_{T,1}^{Jet}$

and sub-leading jet:

$z=p_T^{Track}/p_{T,1}^{Jet}$

$p_T^{Parton}=p_T^{Jet}=p_{T,2(1)}^{Jet}+\Delta p_{T,2(1)}$

If the jet loses energy at larger angles (R>0.3) then the LHC FF measures the jet core fragmenting in vacuum with a reduced jet energy (as the RHIC results suggest)!

# Summary

**Jet quenching measurements at RHIC can be qualitatively explained in a consistent picture by significant broadening and softening of the jet structure favoring a (pQCD-like) partonic energy loss in the medium**

**Suppression of jet $R_{CP}$ as well as significant di-jet energy imbalance observed at the LHC which is balanced at low-$p_T$ at large angles (R>0.8)**

**Jet fragmentation functions (with small R=0.3) are unmodified wrt to p+p, suggesting energy loss followed by vacuum fragmentation outside the medium, consistent with RHIC**

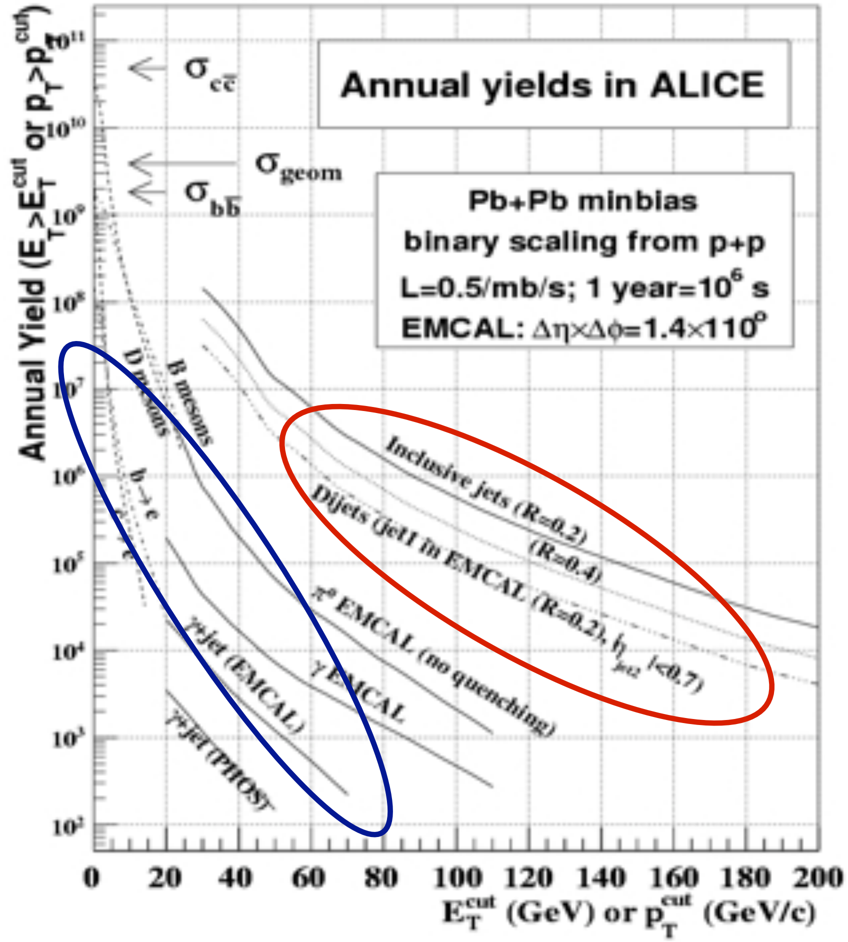
**Is there (qualitative) agreement between the LHC and RHIC results!?**
**(We are comparing 30GeV vs. 100GeV jets ... but remember also p+Pb reference needed!)**

**Some open issues concerning background corrections should be addressed before drawing strong conclusion!**

# Outlook

**But this is just the start ...**

**Direct γ-Jets at LHC allow access to lower jet energies → connection to RHIC**



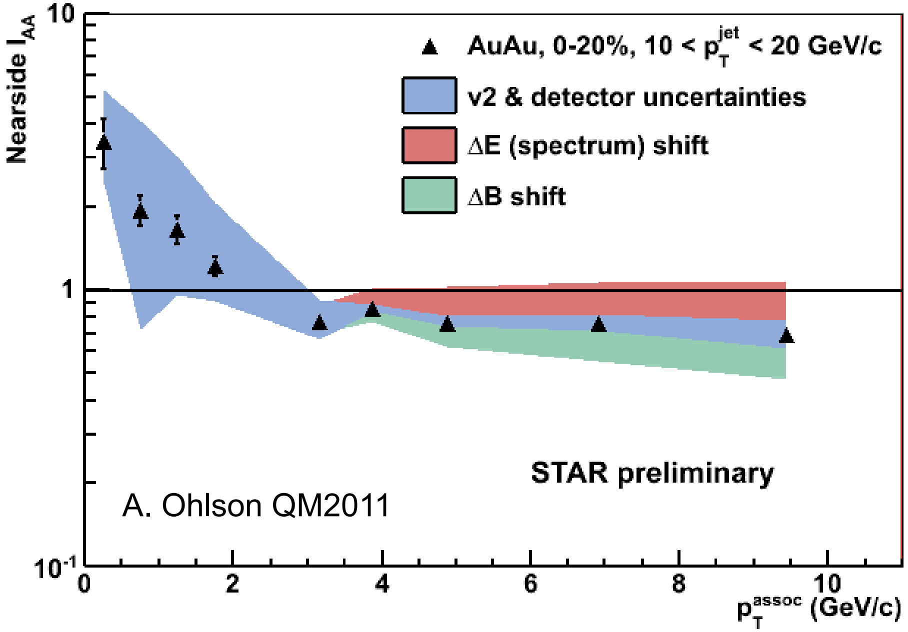

**The landscape of hard probes is rich and exciting!**

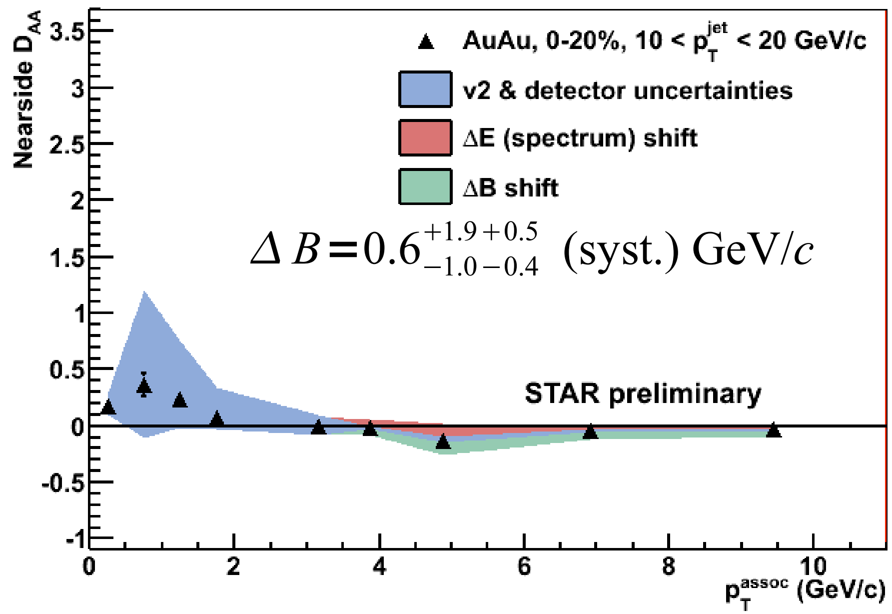
Measure heavy quark energy loss (b-tagged jets) with RHIC upgrades and at the LHC, still open theoretical issue to describe heavy and light flavor energy loss in a consistent framework!

# Backup

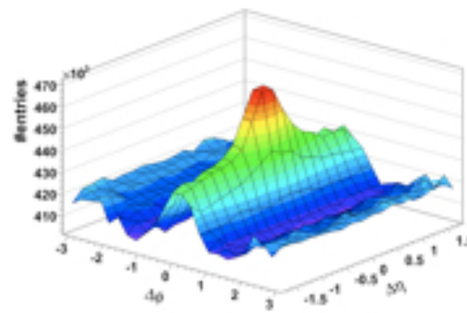
# JH: Near-side $I_{AA}$ and energy balance $D_{AA}$ ...

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc} \qquad \Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$




- **Jet broadening on trigger/near-side!**
- **Enhancement at low pT (pT<2-3 GeV): bkg. biases and/or bulk effects $v_3$ !?**

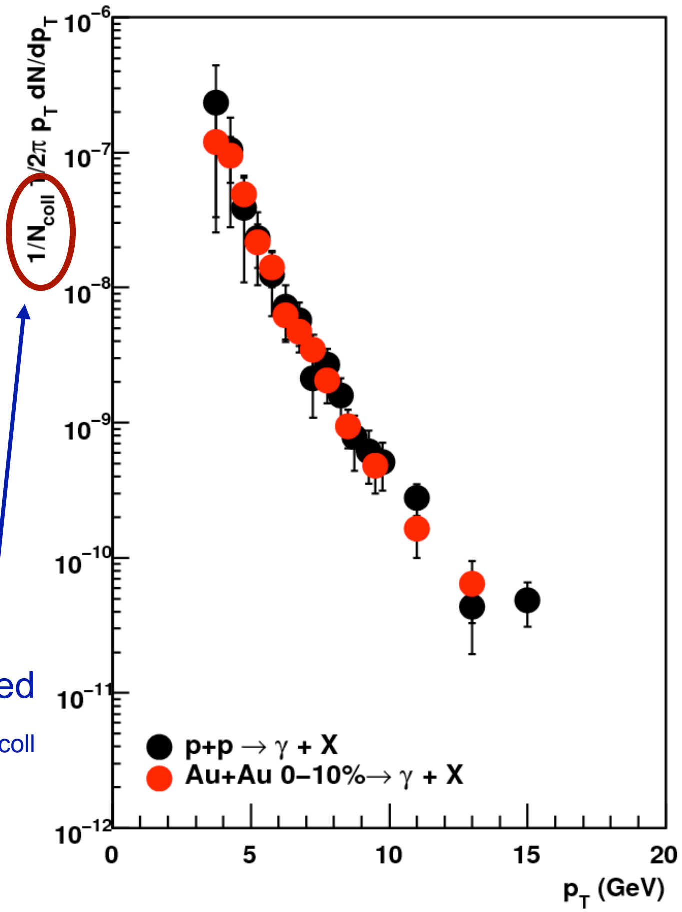


**Both scenarios included in systematic uncertainties!**

Remark: No higher harmonics included in background subtraction! $v_n$ for jets not really determined! Open issue!

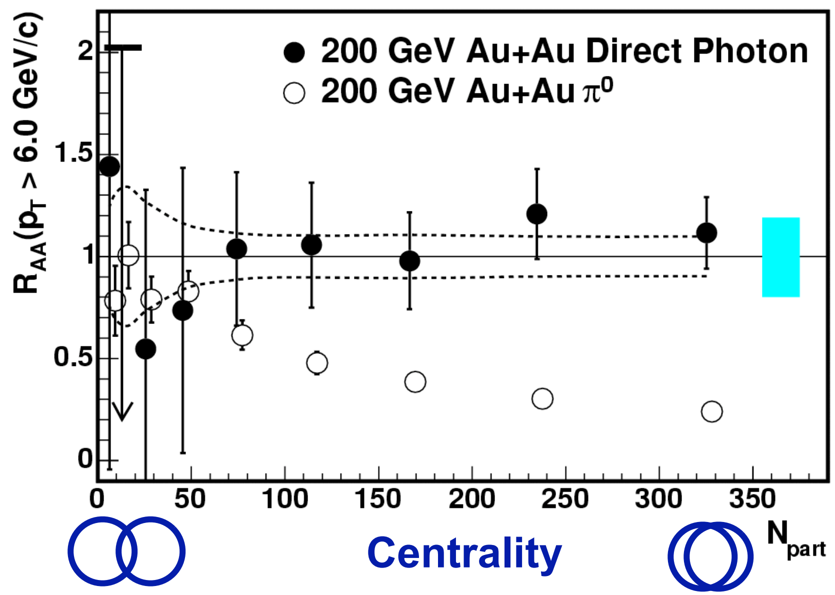
# Test $N_{coll}$ scaling with direct photons

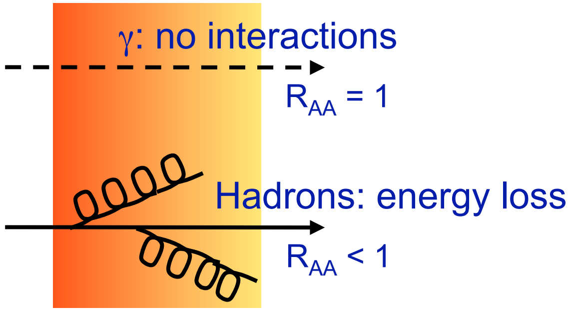
Direct γ spectra




Scaled by $N_{coll}$

PHENIX, PRL 94, 232301

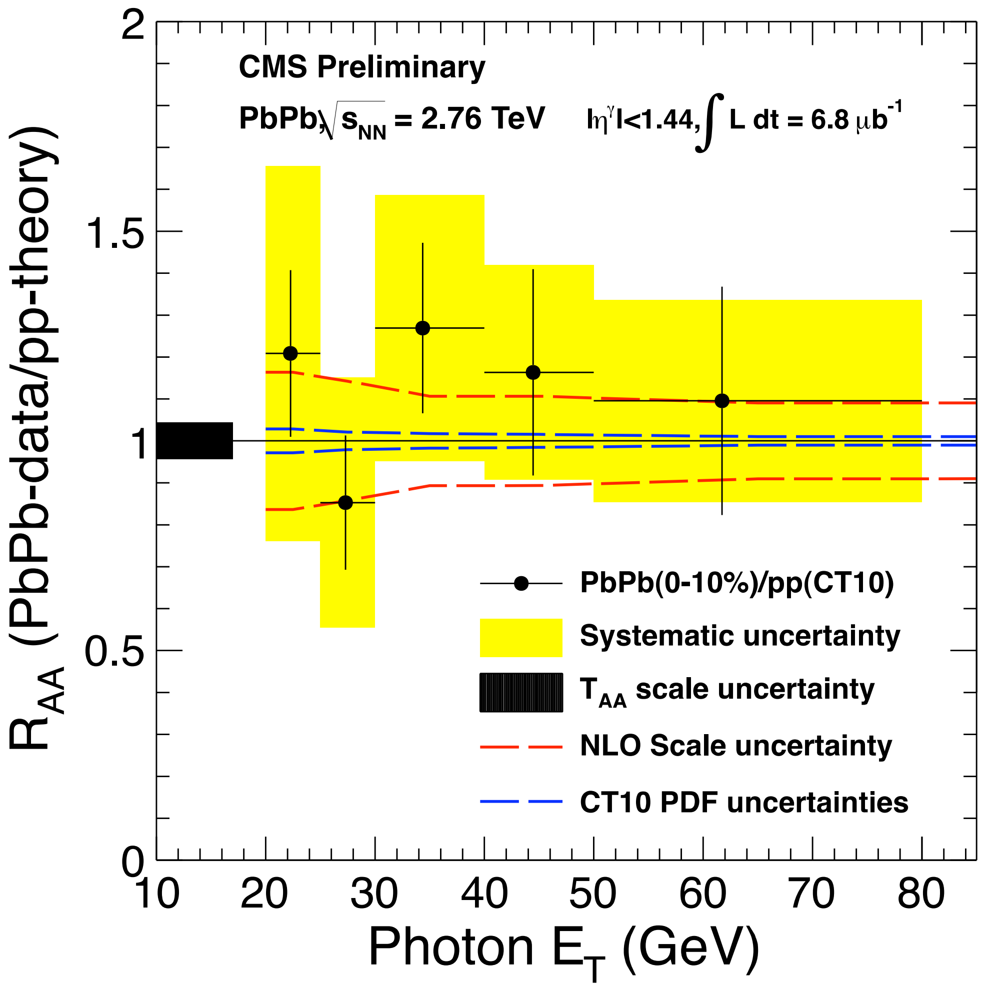


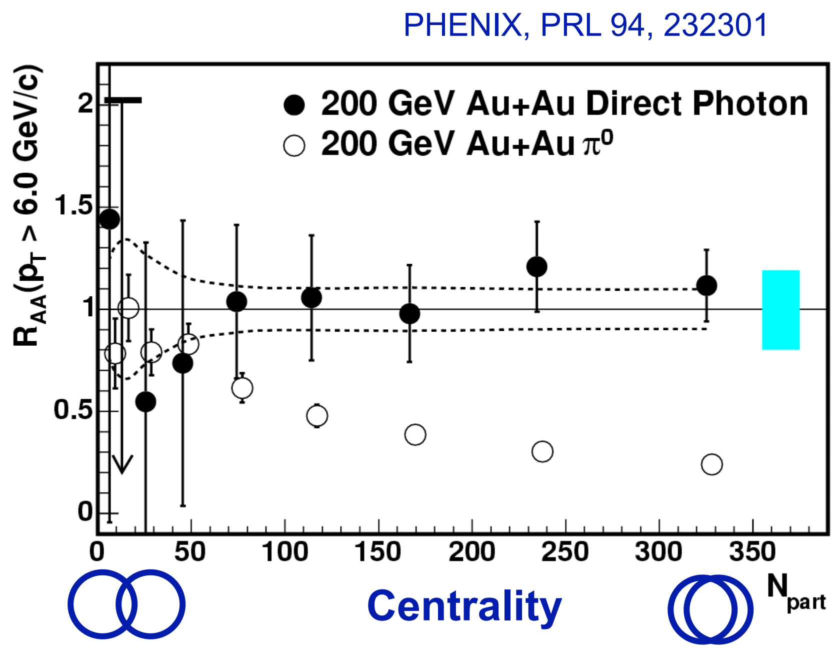



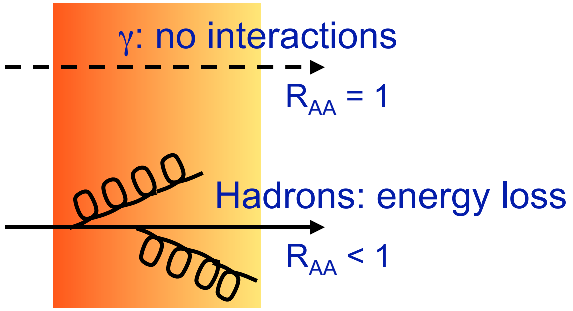

**Direct γ in A+A scales with $N_{coll}$**

**A+A initial state is incoherent superposition of p+p for hard probes**

# Test $N_{coll}$ scaling with direct photons



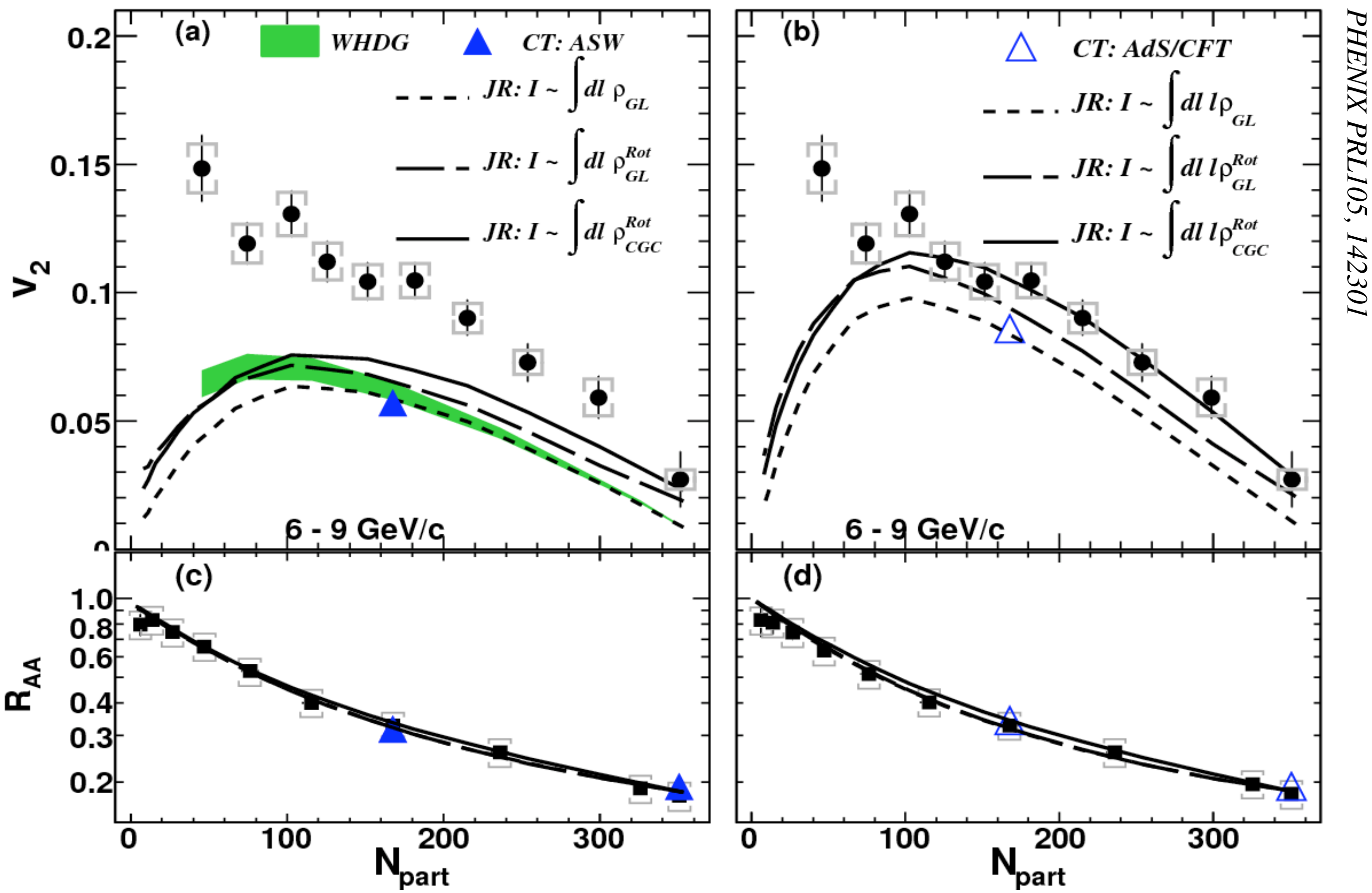




**Direct γ in A+A scales with $N_{coll}$**

**A+A initial state is incoherent superposition of p+p for hard probes**

# Path length dependence and $v_2$

$\Delta E \propto \hat{q}\, L^2$ $\Delta E \propto \hat{q}\, L^3$




**$v_2$ at high $p_T$ due to energy loss**

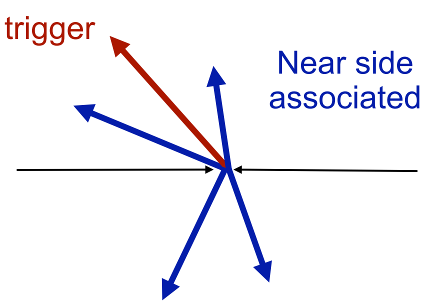
Most calculations give too small effect, still an open issue.
Also experimentally, need to measure “jet $v_2$”

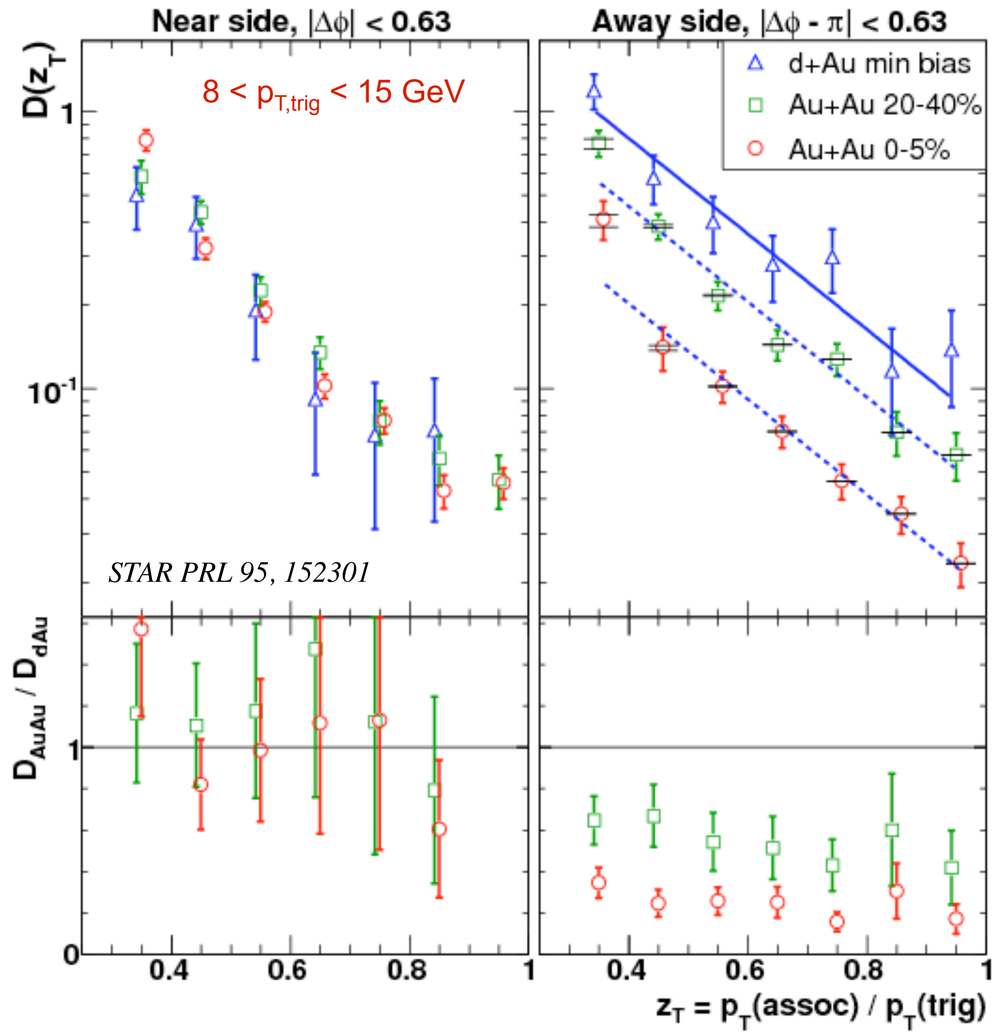
# Di-hadron yield suppression at high-$p_T$

$8 < p_T^{trig} < 15$ GeV

## Near side

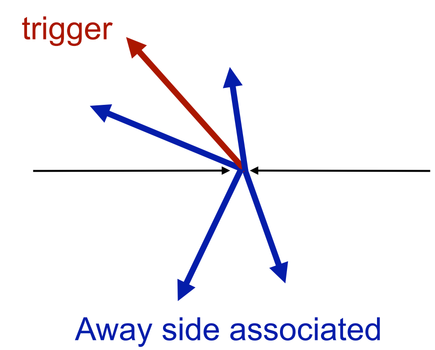
Yield of additional particles in the jet




## Away side

Yield in balancing jet, after energy loss




**<u>Near side:</u> No modification**

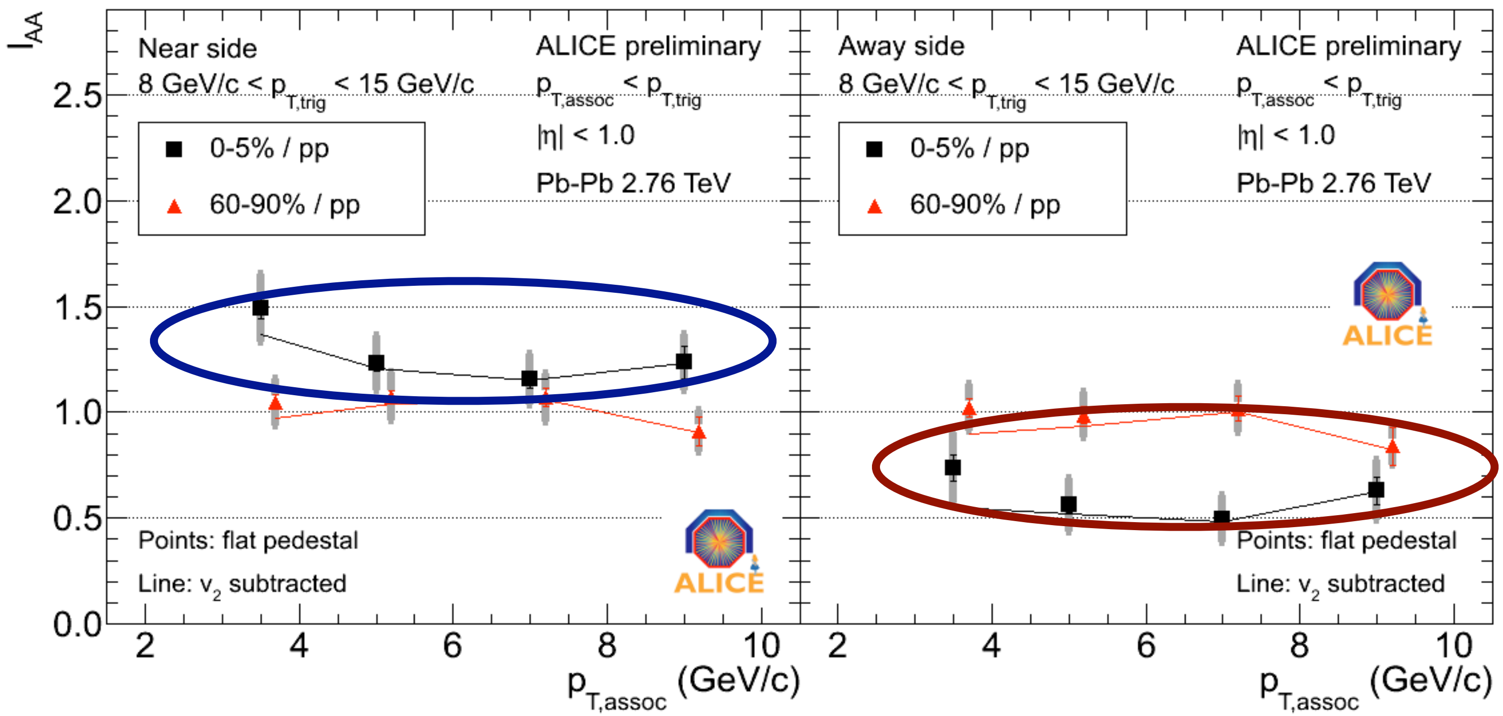
**⇒ Fragmentation outside medium?**

**<u>Away-side:</u> Suppressed by factor 4-5**

**⇒ large energy loss**

**But no shape modification in $z_T$!**

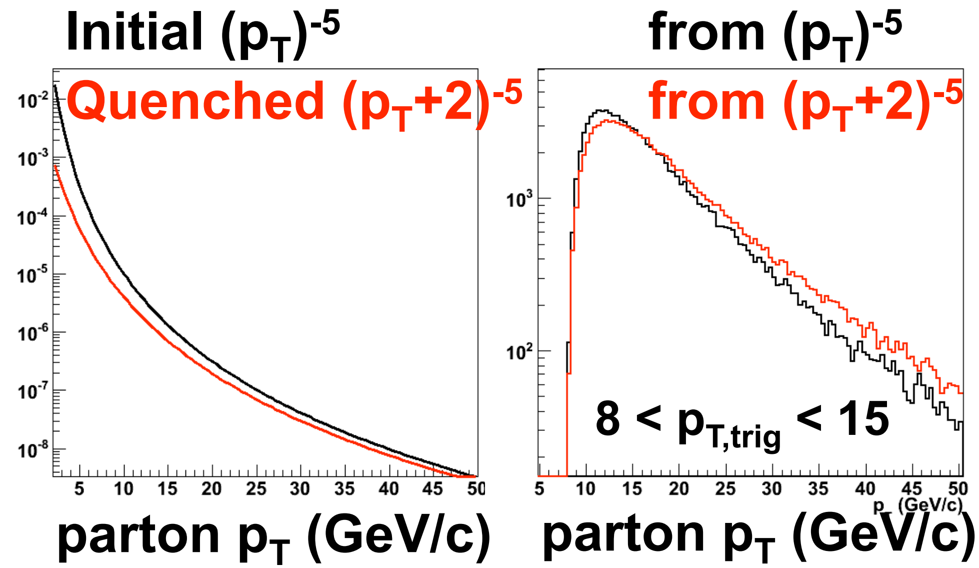
# High-$p_T$ di-hadron correlations at the LHC



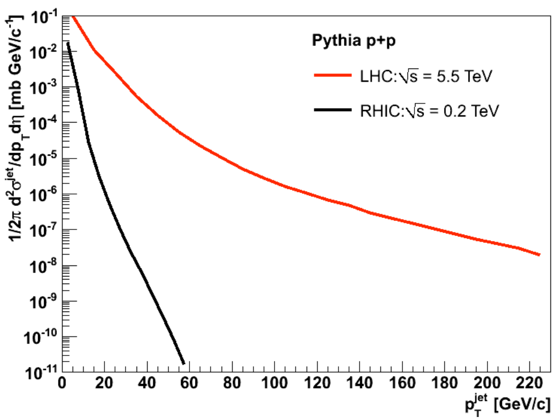

**Near-side of central events slightly enhanced $I_{AA}$ ~ 1.2!**

**Away side of central events suppressed: $I_{AA}$ ~ 0.6**
**less than RHIC, but similar to RHIC no shape modification**

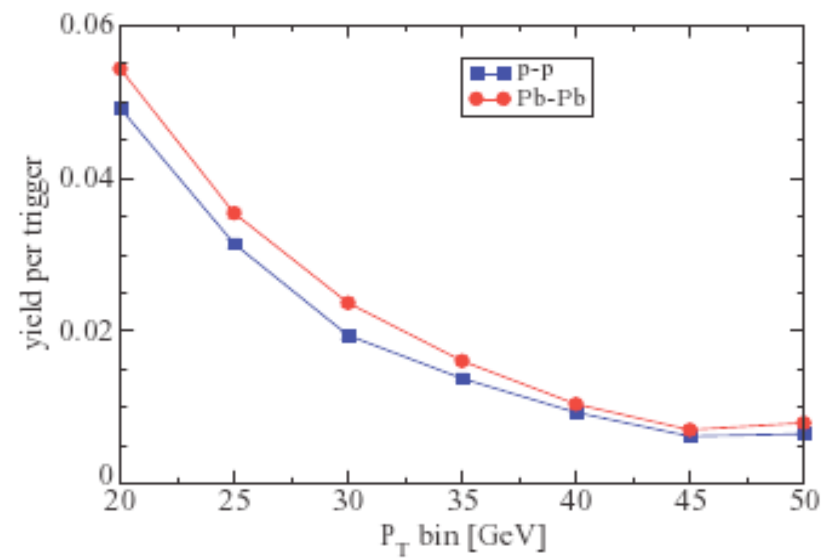
# Near-side $I_{AA}$ enhancement at the LHC ...




RHIC, steeper, more exponential spectrum does not change the shape $I_{AA}$~1, harder (more power law) spectrum at LHC leads to $I_{AA}$>1




*T Renk, PRC 77, 044905 (2008)*

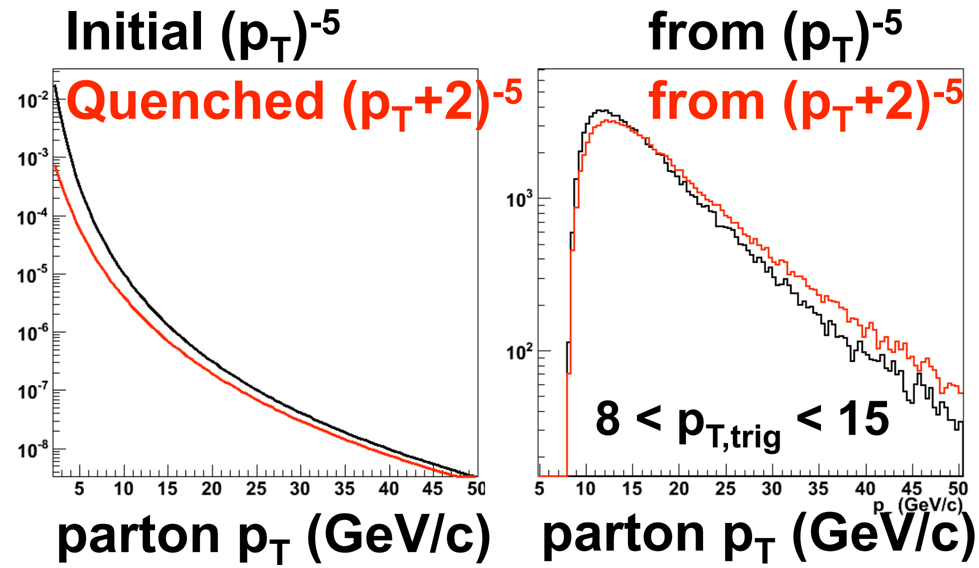


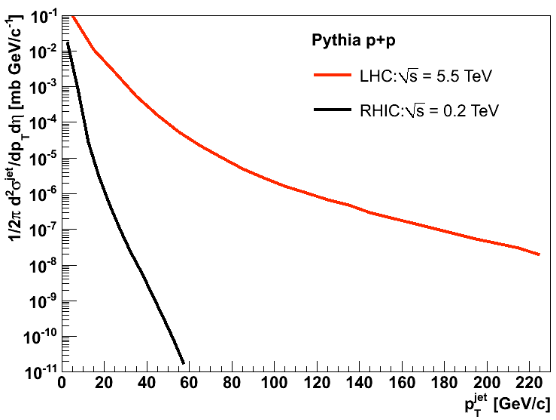

Larger energy loss of gluons in the medium and harder fragmentation of quarks

# Near-side $I_{AA}$ enhancement at the LHC ...

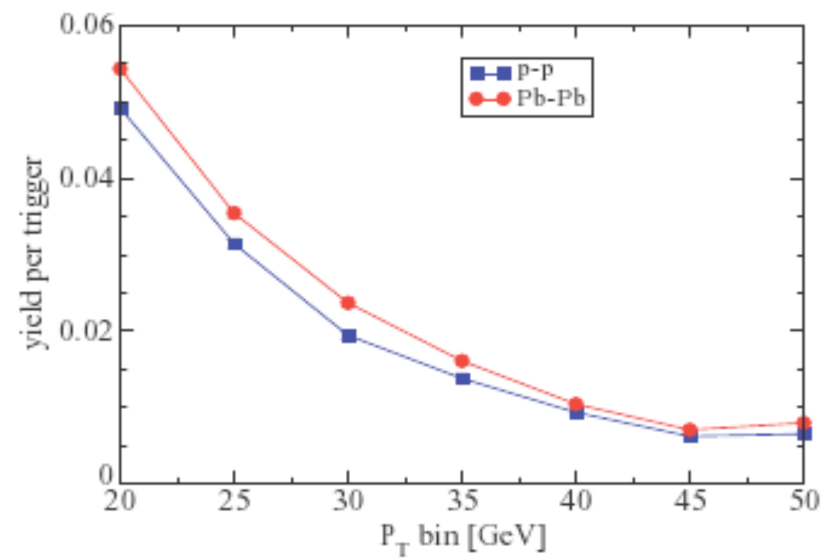
Same trigger $p_T$ in Pb+Pb collisions probes a different parton spectrum than in p+p collision

RHIC, steeper, more exponential spectrum does not change the shape $I_{AA}$~1, harder (more power law) spectrum at LHC leads to $I_{AA}$>1



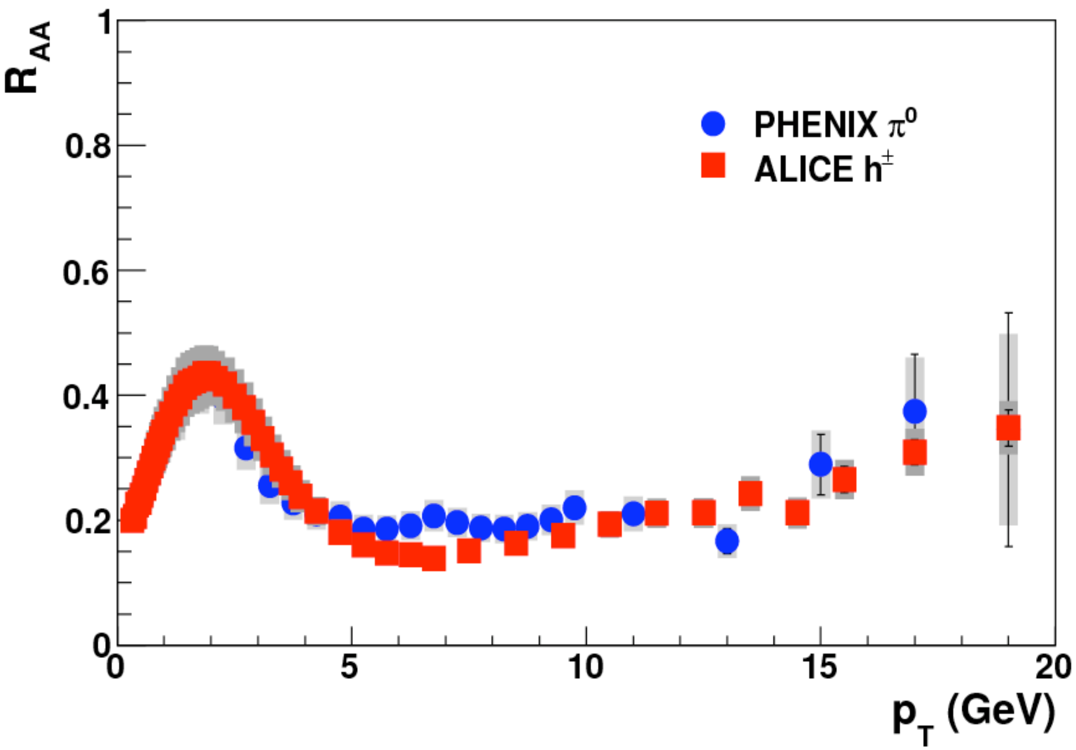



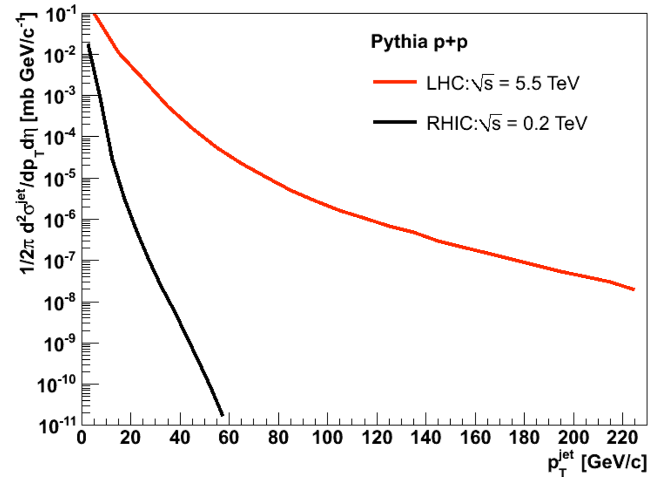

*T Renk, PRC 77, 044905 (2008)*




Larger energy loss of gluons in the medium and harder fragmentation of quarks

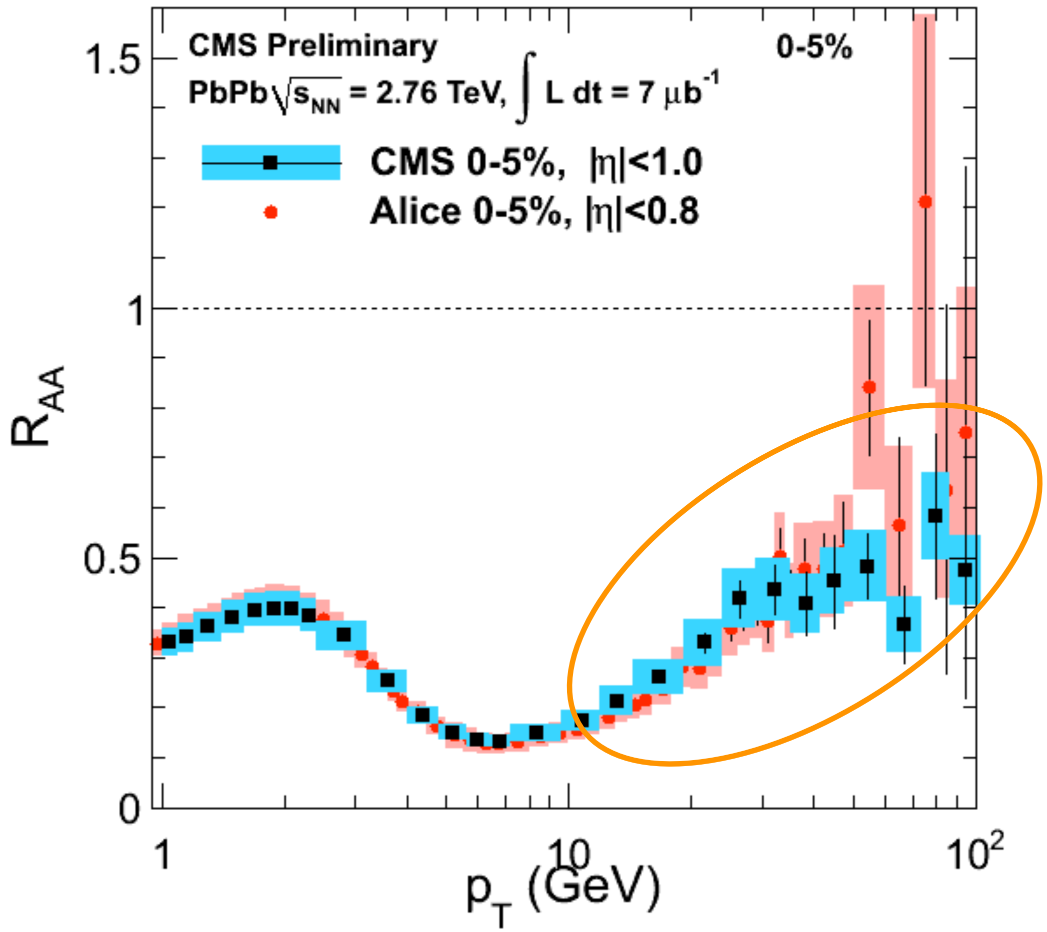
# Nuclear Modification at the LHC




**Similar suppression of $R_{AA}$ at intermediate $p_T$ wrt to RHIC suggests larger energy loss, due to "flatter" jet spectrum**

# Nuclear Modification at the LHC

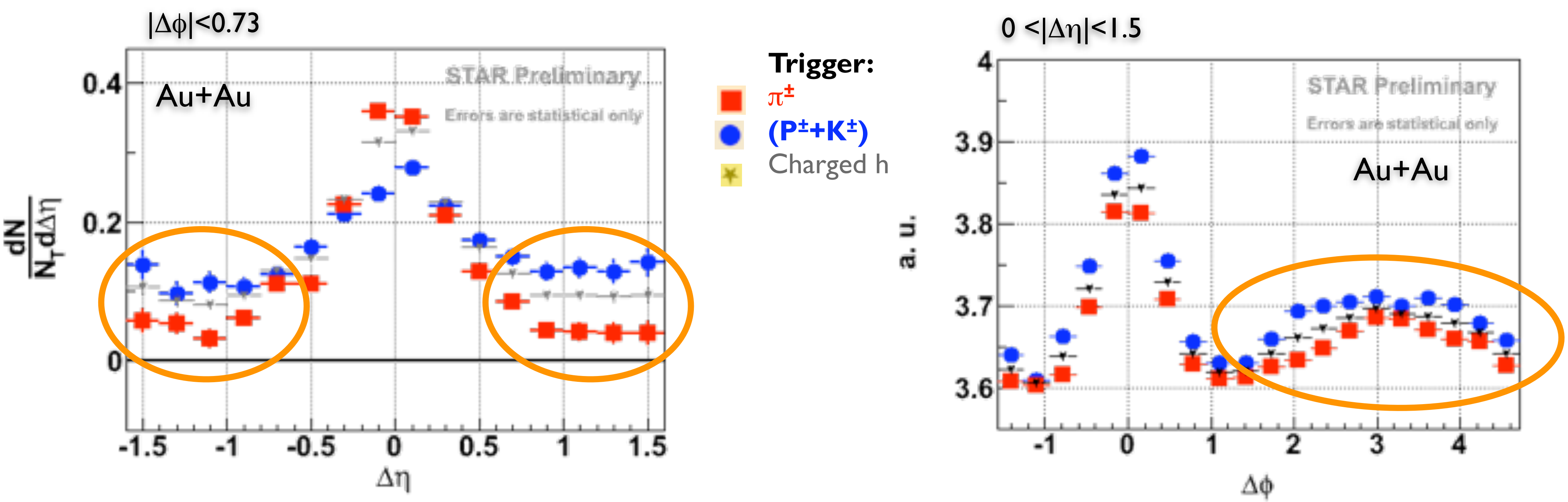



**Similar suppression of $R_{AA}$ at intermediate $p_T$ wrt to RHIC suggests larger energy loss, due to "flatter" jet spectrum**

**Rise of $R_{AA}$ at high $p_T$ suggests a radiative energy loss picture**

# The ridge/$v_3$ for "high-$p_T$" trigger PID

$4 < p_{T,trigger} < 6$ GeV/c and $p_{t,assoc.} > 1.5$ GeV/c



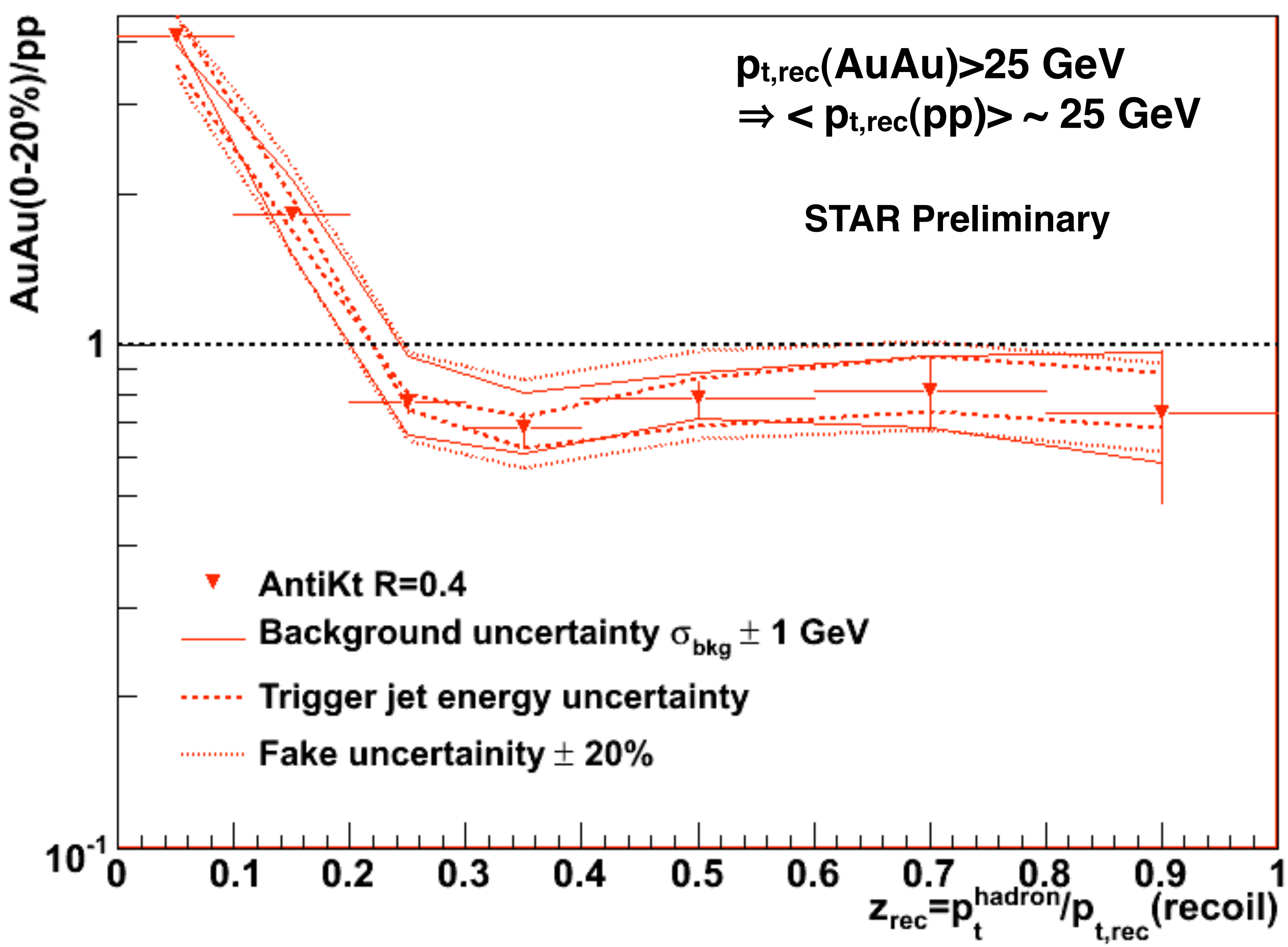

**Near-side:** Larger ridge/$v_3$ effect for protons as compared to pion
Jet peak larger for pions, also seen in d+Au

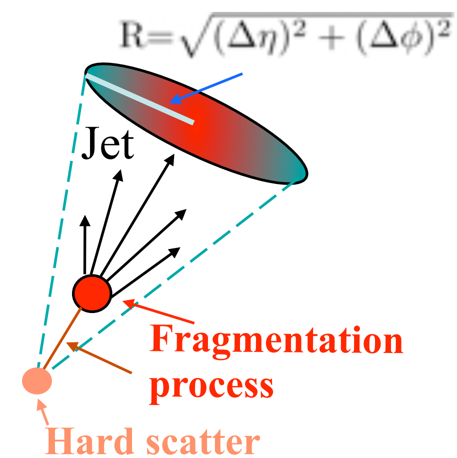
**Away-side:** Difference in away-side structure between protons and pions
$v_3$ more visible for proton triggers!?
Are we sampling with proton triggers from recombination more of the bulk in this kinematic? Or other effects?
Can be checked with protons at higher $p_T$!

# Recoil "Fragmentation Function" in Au+Au collisions

large uncertainties due to background
(further systematic evaluation needed)

E. Bruna QM2009

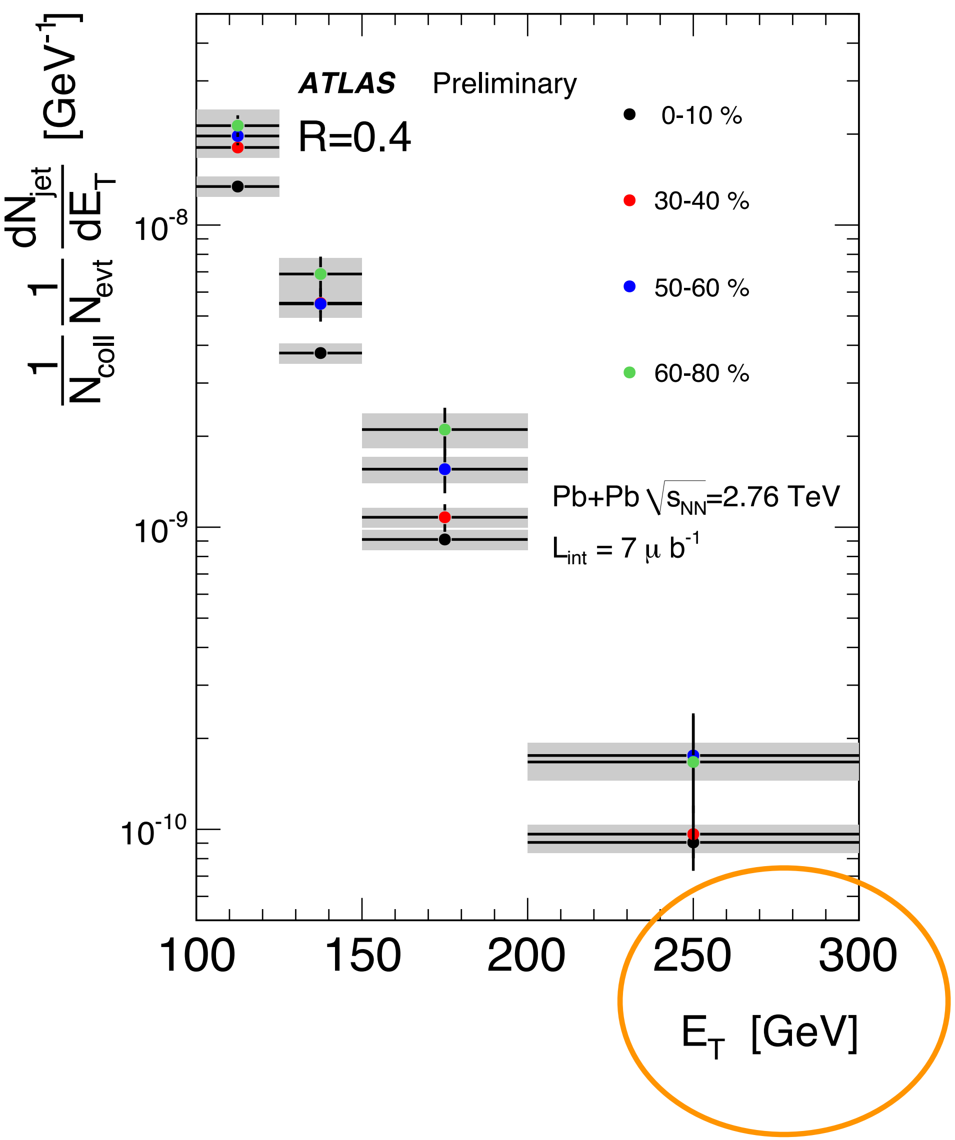


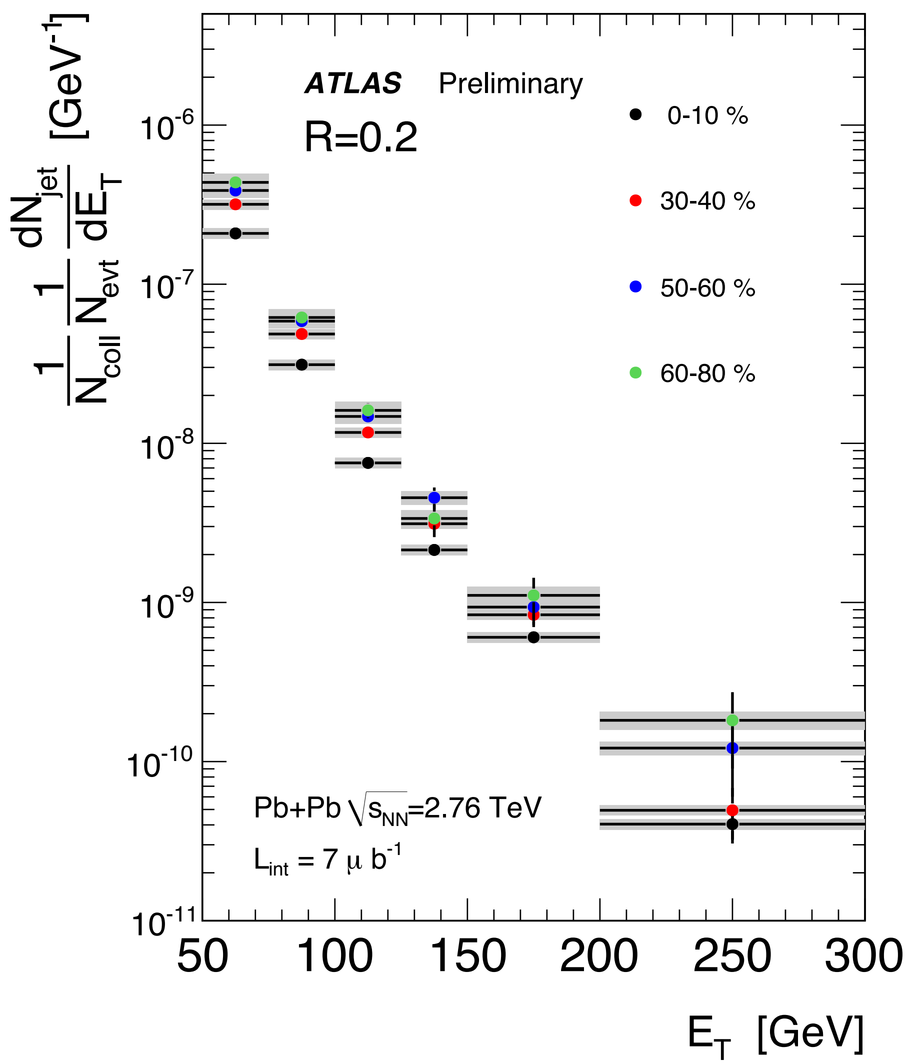

**Small/"no" modification in the "fragmentation function" for jet $p_t$ < $p_{t,rec}$(pp)> ~ 25 GeV at high z!**

# First year LHC: Jet x-section!

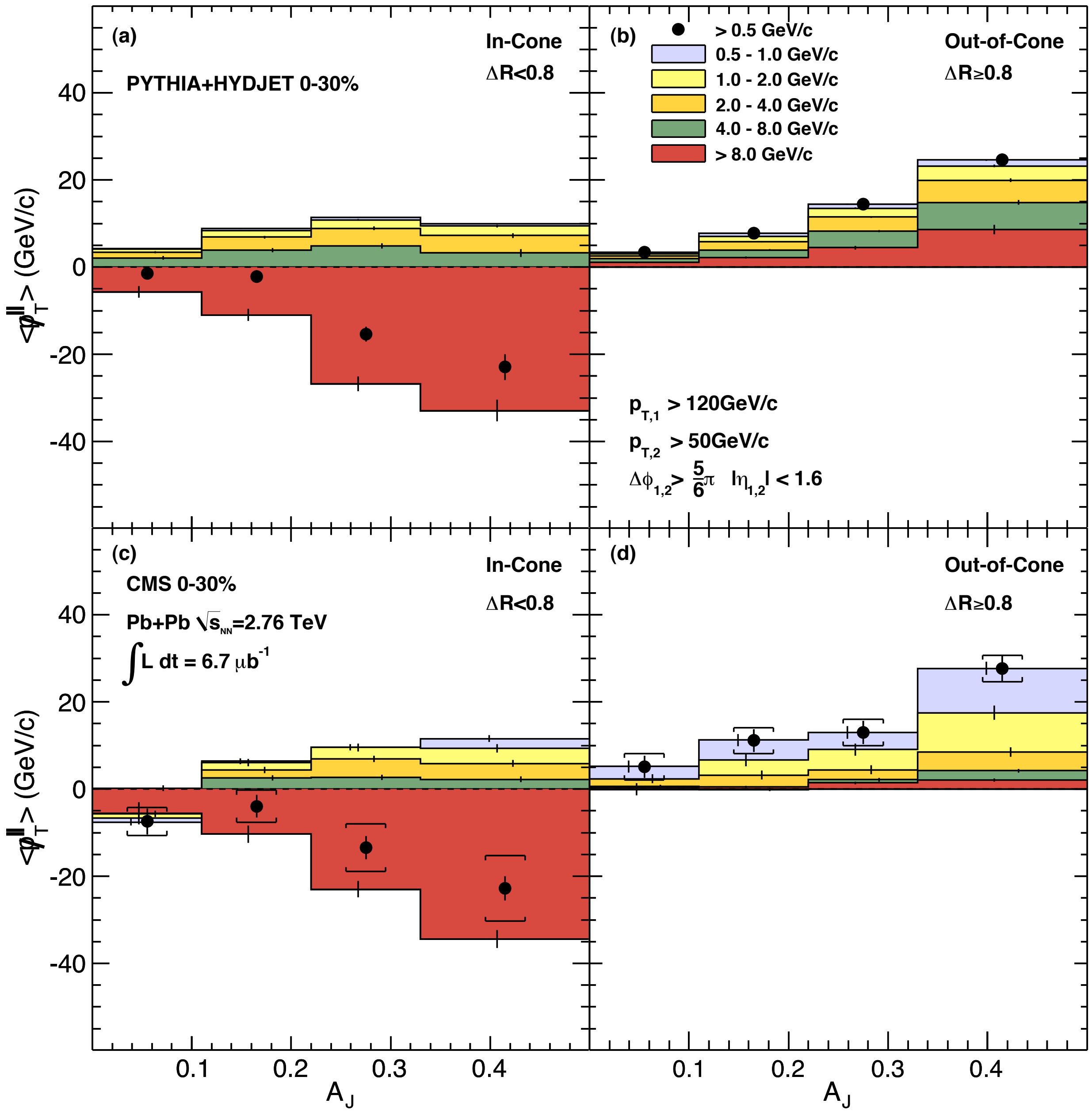
R=0.4



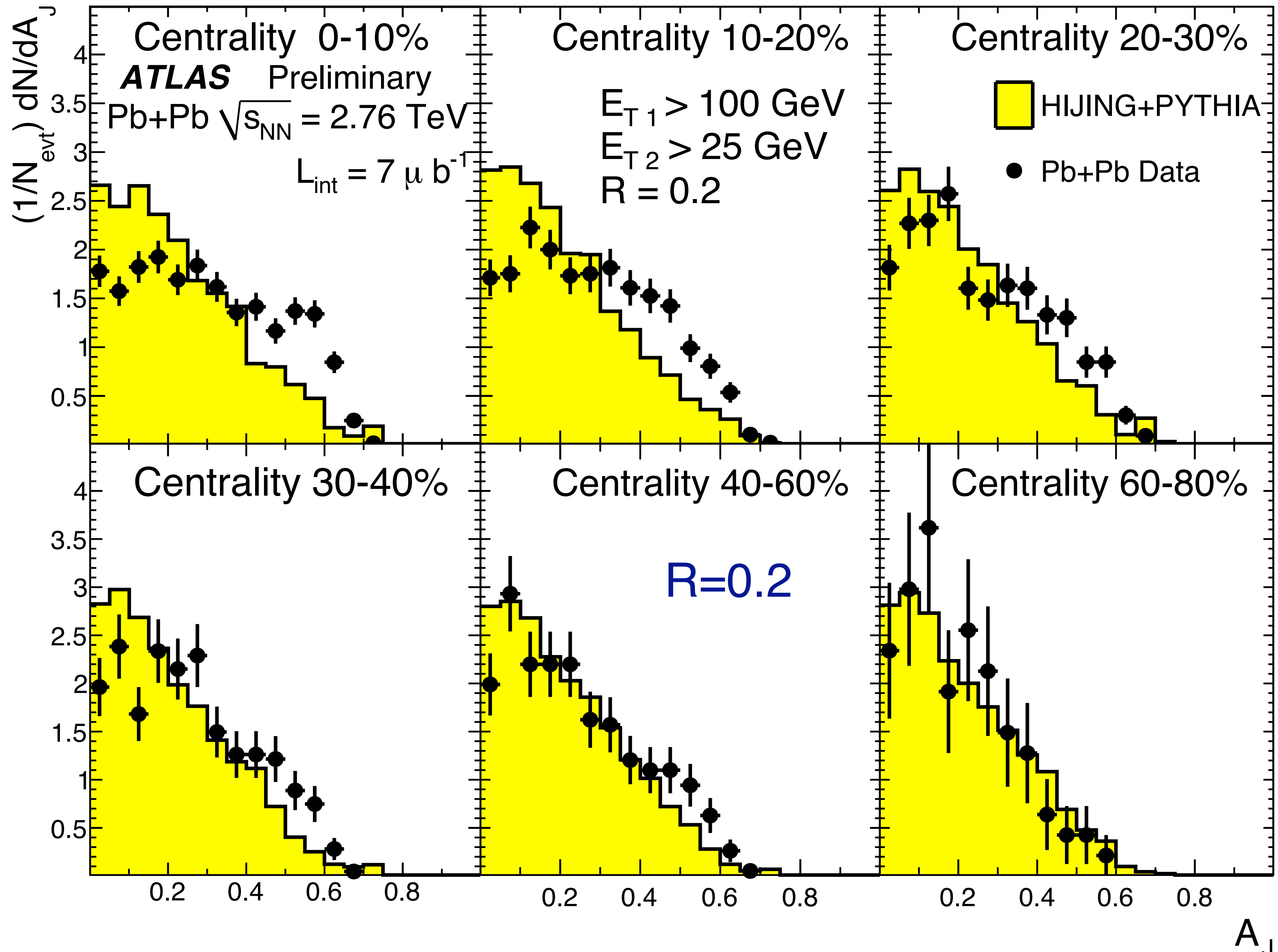

R=0.2



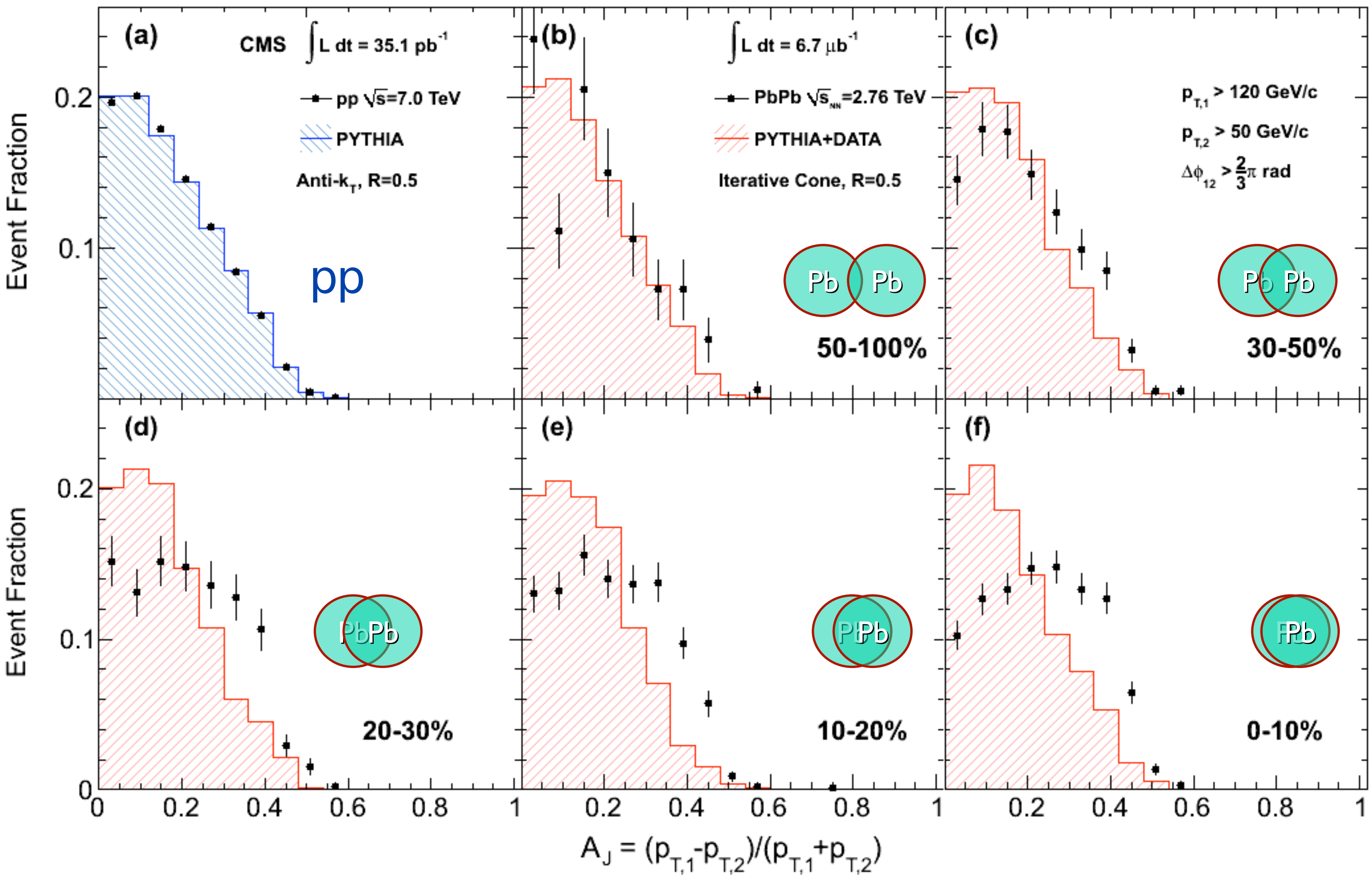
# Missing $p_T^{||}$


(a)
In-Cone
ΔR<0.8
PYTHIA+HYDJET 0-30%
(b)
> 0.5 GeV/c
0.5 - 1.0 GeV/c
1.0 - 2.0 GeV/c
2.0 - 4.0 GeV/c
4.0 - 8.0 GeV/c
> 8.0 GeV/c
Out-of-Cone
ΔR≥0.8
p_T,1 > 120GeV/c
p_T,2 > 50GeV/c
Δφ_1,2 > 5/6 π |η_1,2| < 1.6
(c)
CMS 0-30%
Pb+Pb √s_NN=2.76 TeV
∫L dt = 6.7 μb^-1
In-Cone
ΔR<0.8
(d)
Out-of-Cone
ΔR≥0.8
<p_T^||> (GeV/c)
A_J
40
20
0
-20
-40
0.1
0.2
0.3
0.4

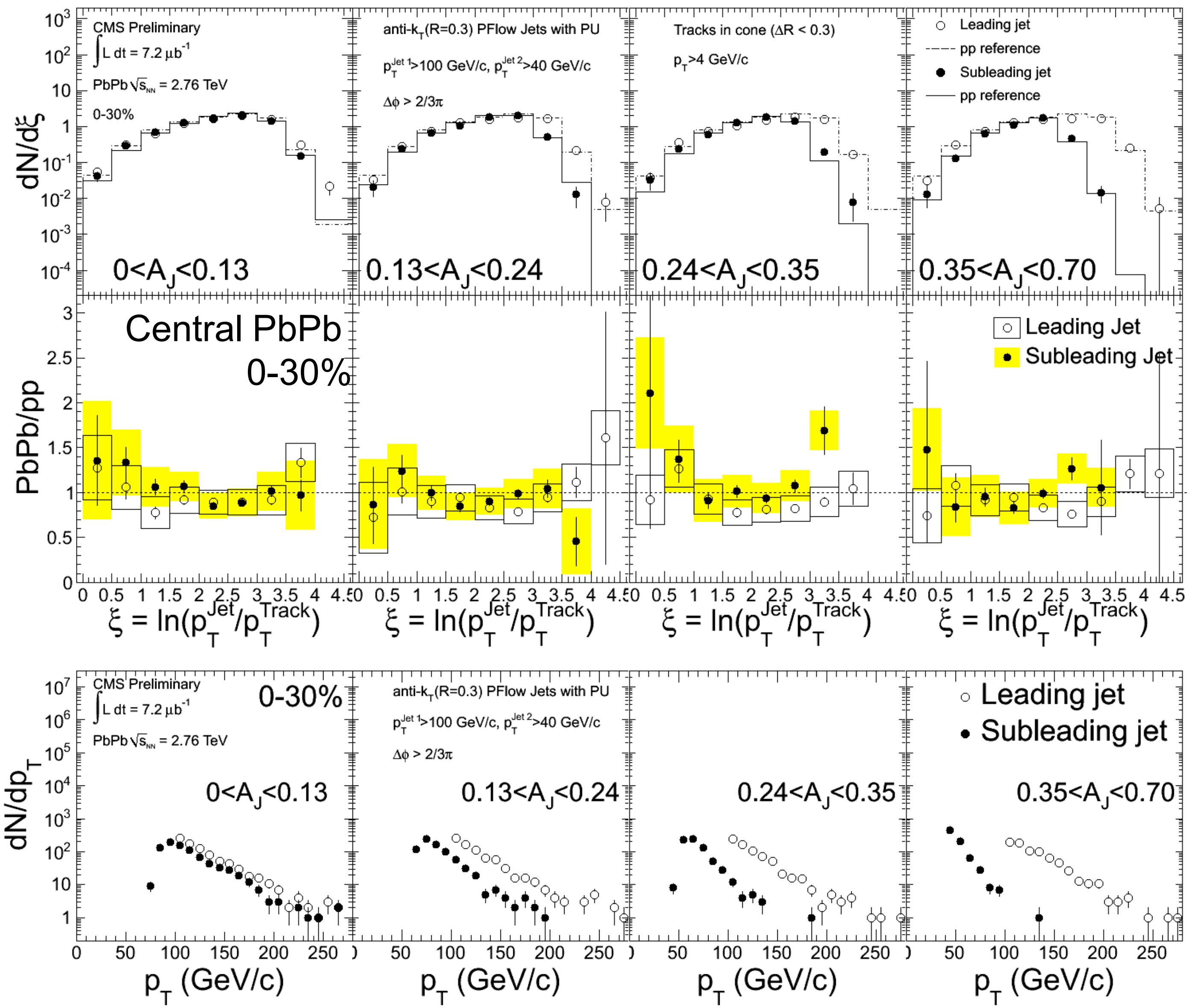
# Di-jet asymmetry ATLAS R=0.3

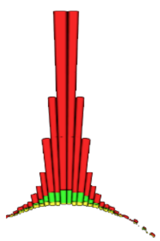


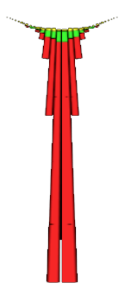
# Di-jet asymmetry CMS R=0.5



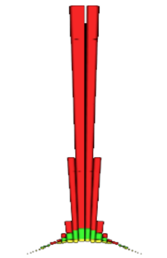
# FF vs. $A_j$

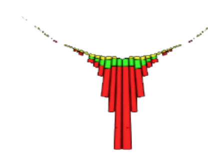






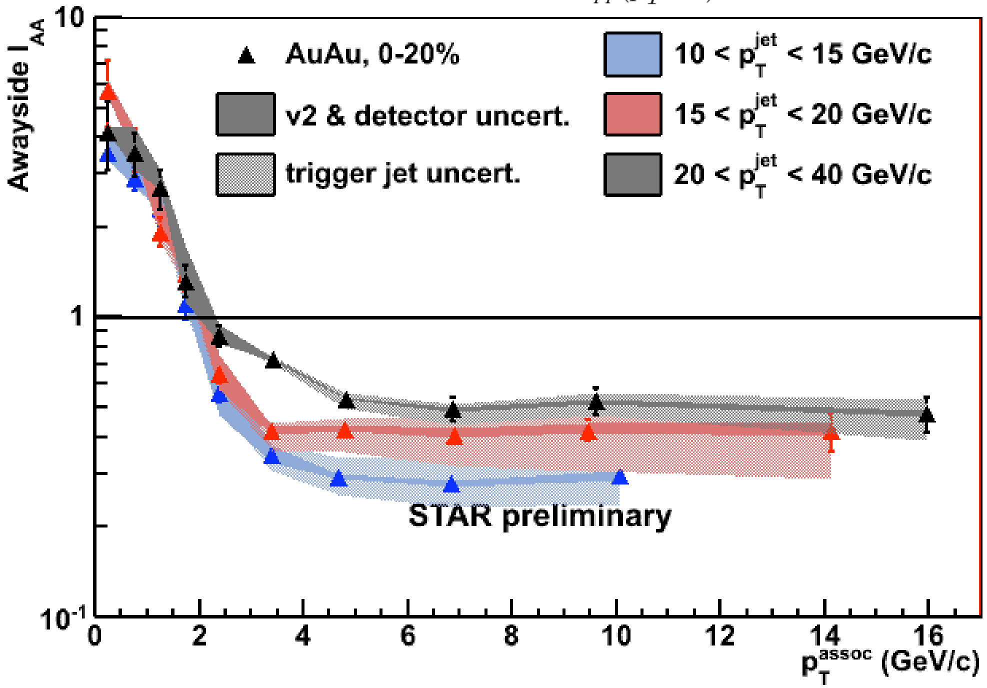

CMS Preliminary
∫L dt = 7.2 μb⁻¹
PbPb √s_NN = 2.76 TeV
0-30%
anti-k_T(R=0.3) PFlow Jets with PU
p_T^Jet 1>100 GeV/c, p_T^Jet 2>40 GeV/c
Δφ > 2/3π
Tracks in cone (ΔR < 0.3)
p_T>4 GeV/c
Leading jet
pp reference
Subleading jet
pp reference
0<A_J<0.13
0.13<A_J<0.24
0.24<A_J<0.35
0.35<A_J<0.70
dN/dξ
Central PbPb
0-30%
Leading Jet
Subleading Jet
PbPb/pp
ξ = ln(p_T^Jet/p_T^Track)
dN/dp_T
p_T (GeV/c)

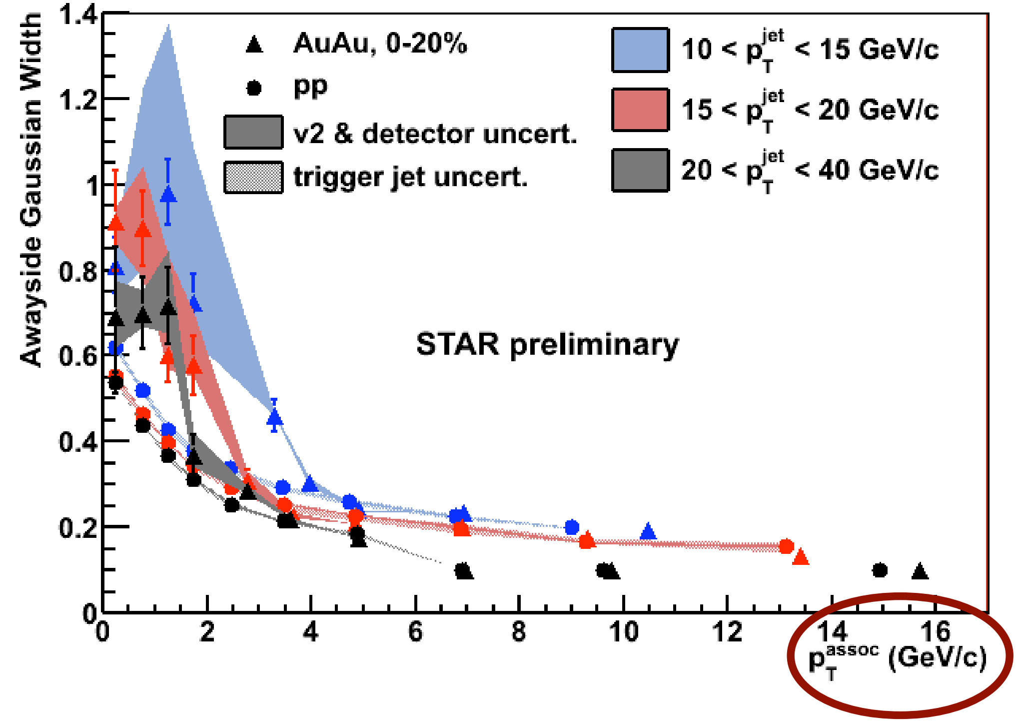





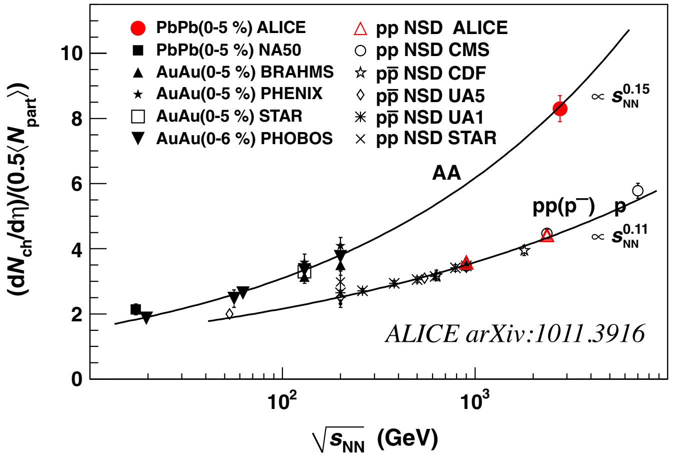
# JH: $I_{AA}$ and width vs. jet energy

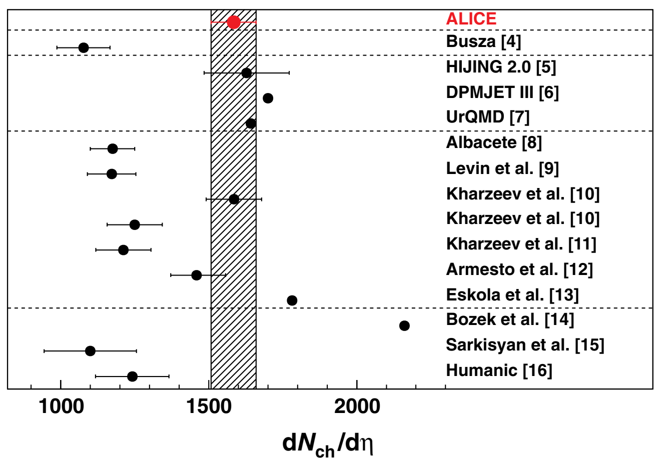
$$I_{AA}(p_T^{assoc}) = \frac{Y_{AA}(p_T^{assoc})}{Y_{pp}(p_T^{assoc})}$$



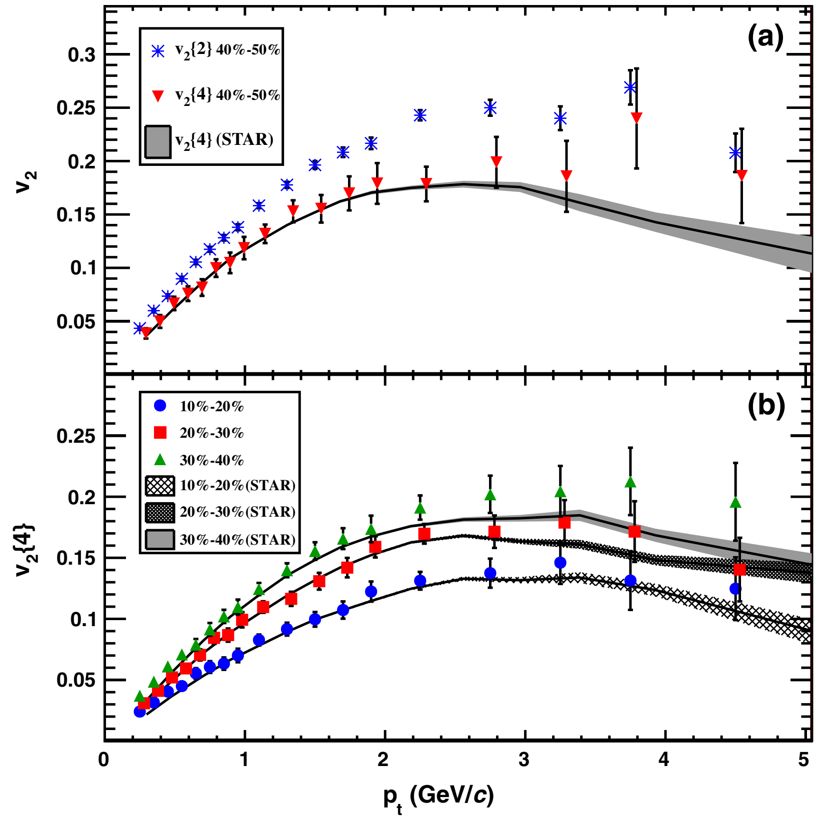



# Bulk properties at the LHC (ALICE)

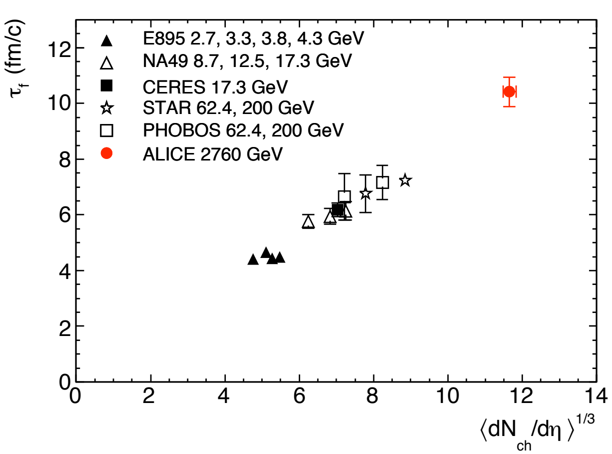


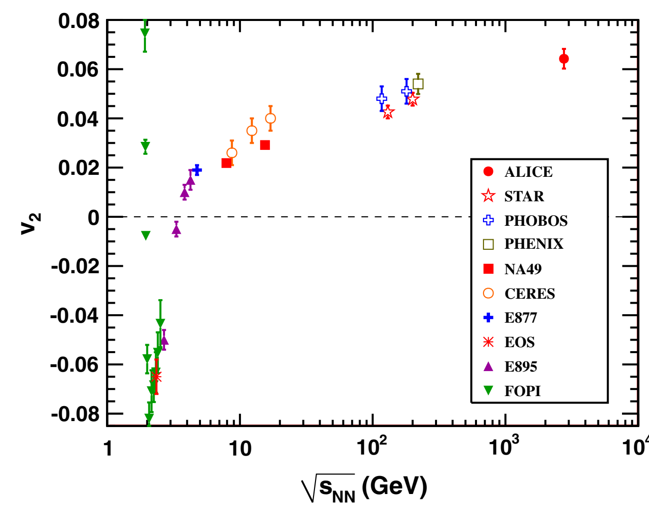




ALICE arXiv:1011.3914




ALICE arXiv:1012.4035



# Jet Spectrum Unfolding and Corrections

**Corrections for smearing of jet $p_t$ due to HI bkg. nonuniformities:**

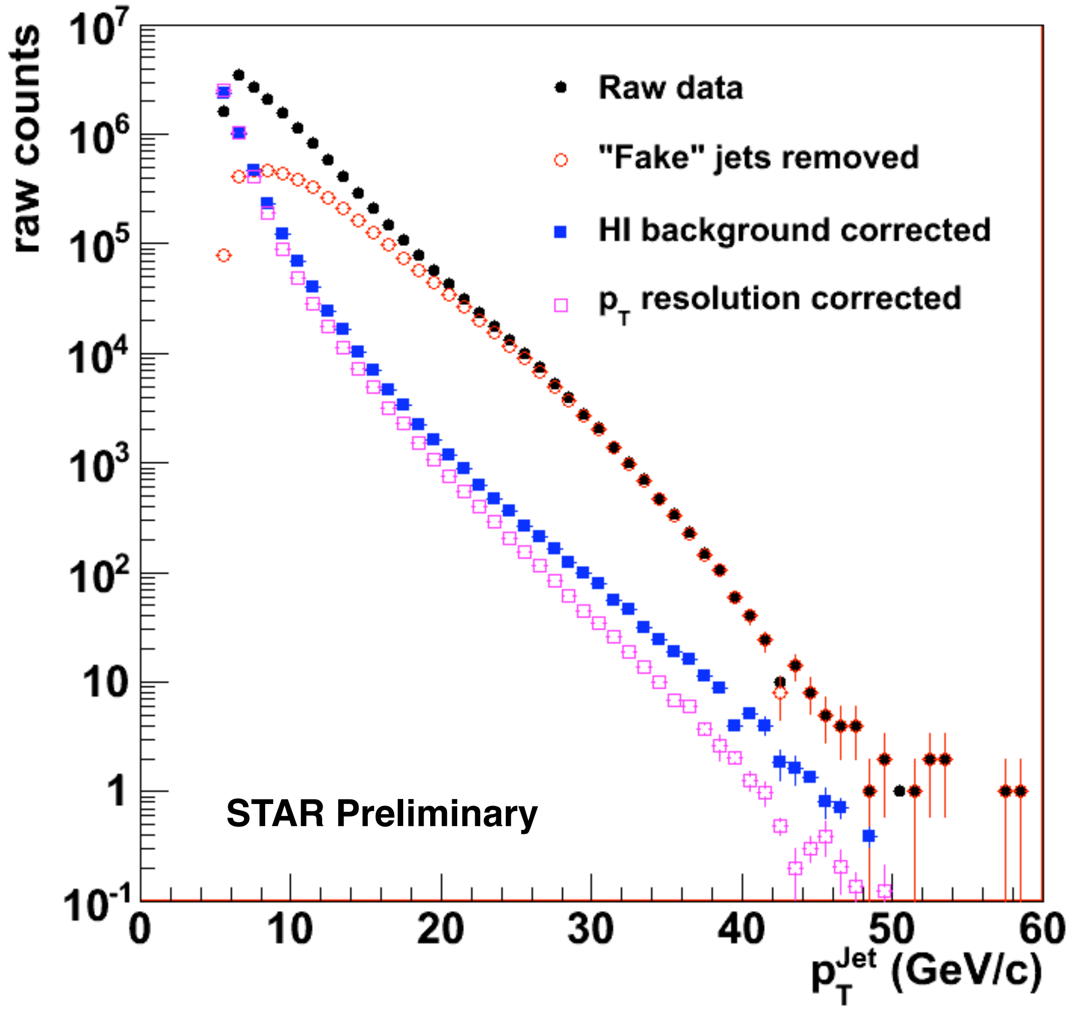
1) raw spectrum

2) removal of “fake”-
jet correlations
(via randomizing HI event)

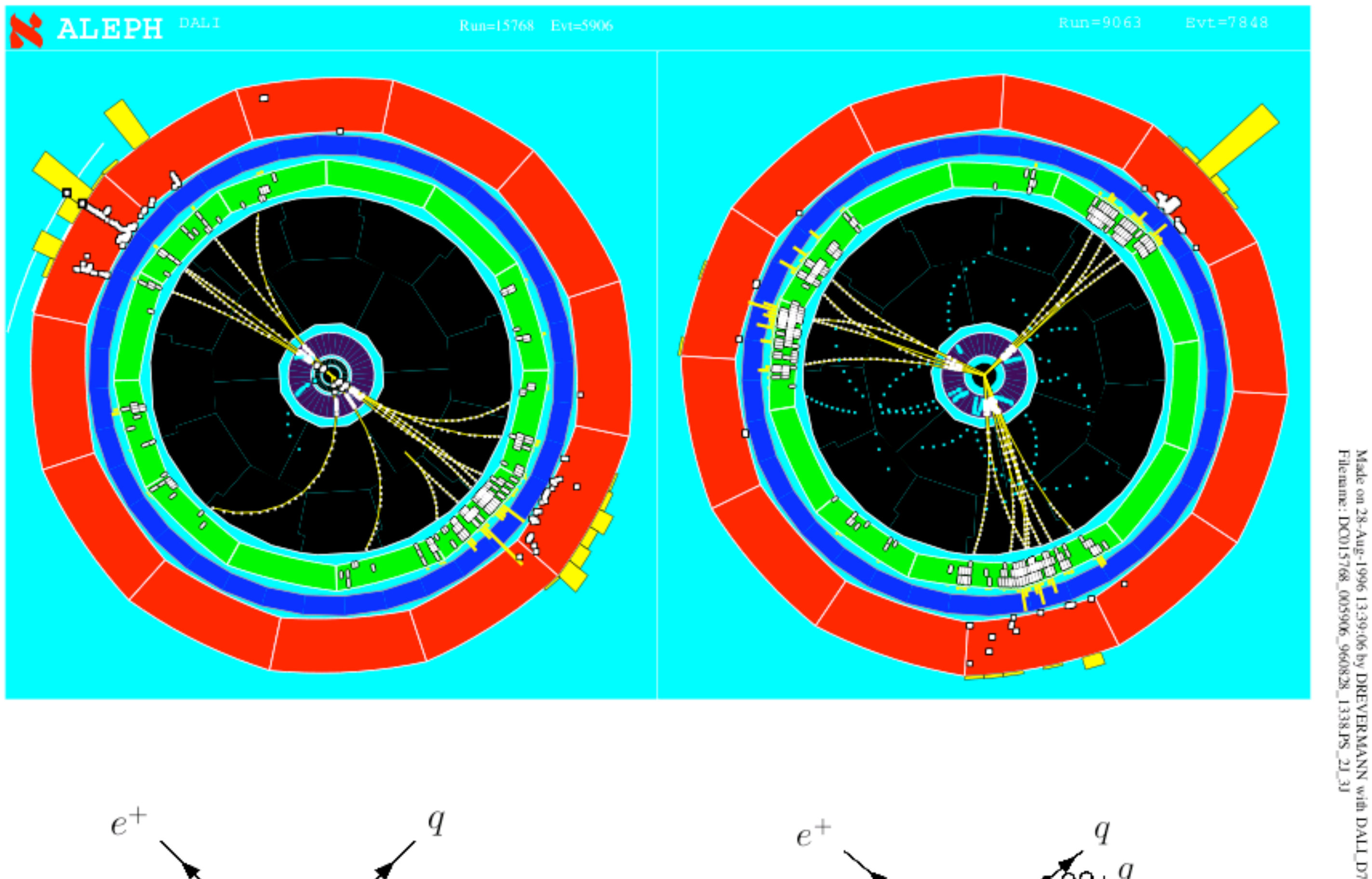
3) unfolding (bayesian) of
HI bkg. fluctuations
(gaussian approximation)

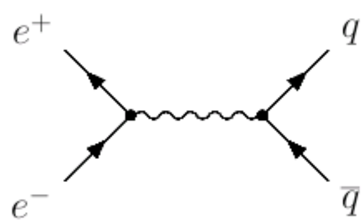
4) correction for $p_T$ resolution

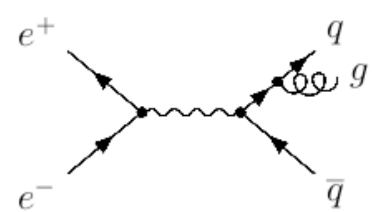
M.Ploskon QM2009



# Jets: “Seeing” quarks and gluons (partons)




**In high-energy collisions, observe the fragments of quarks, gluons (‘jets’)**
**The energy sum of all the fragments = jet energy = parton energy!**